The University of Reading

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Numerical Weather Prediction

An Overview of high resolution UM performance for CSIP cases

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Abstract

The Convective Storms Initiation Project (CSIP) is a joint project involving a number of UK Universities (funded by the NERC Centres for Atmospheric Science, NCAS), the NCAS Universities' Facility for Atmospheric Measurement (UFAM), the Institute for Meteorology and Climate Research (IMK) Karlsruhe, Germany and the Met Office. The objective of the project is to improve our understanding of the mechanisms which determine precisely when and where individual deep convective clouds initiate. The experiment is focussed over the UK, and it is anticipated that, while the potential mechanisms are similar to those found elsewhere, the dominant mechanisms will be determined by the maritime climate and local topography of the UK. This is the first in-depth observational study of deep convection over the UK for several decades.

During the 2005 campaign, the UK 4 km model was quasi-operational, and it provided some guidance for operations. However, post event the 'High Resolution Trial Model' (HRTM) system was run to provide a first pass indication of performance of 4 km and 1 km models. The purpose of this document is to give a very brief overview of model performance, and, hopefully, to identify any aspects of the model which appear to show systematic error, to identify those aspects of IOPs which are of interest and a priority order for analysis.

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1 Introduction

The Convective Storms Initiation Project (CSIP) is a joint project involving a number of UK Universities (funded by the NERC Centres for Atmospheric Science, NCAS), the NCAS Universities' Facility for Atmospheric Measurement (UFAM), the Institute for Meteorology and Climate Research (IMK) Karlsruhe, Germany and the Met Office. The objective of the project is to improve our understanding of the mechanisms which determine precisely when and where individual deep convective clouds initiate. The experiment is focussed over the UK, and it is anticipated that, while the potential mechanisms are similar to those found elsewhere, the dominant mechanisms will be determined by the maritime climate and local topography of the UK. This is the first in-depth observational study of deep convection over the UK for several decades.

A number of instrument systems were deployed during CSIP (Figure 1). We shall not list them all here (the reader is referred to http://www.env.leeds.ac.uk/csip/ for further detail). However, central to the experiment were three systems:

1. The Chilbolton steerable radar system, comprising two radars, a conventional S-band (3 GHz) radar suitable for sensing hydrometeors but also capable of seeing other features, and a 'clear air' (1250 MHz) radar which primarily sees Bragg backscatter from variations in refractive index mainly induced by moisture gradients, as well as more conventional Rayleigh scatter. Both systems are dual polarisation, Doppler.
2. A network of 5 or 6 radiosonde stations with ~100 km spacing releasing sondes typically every hour

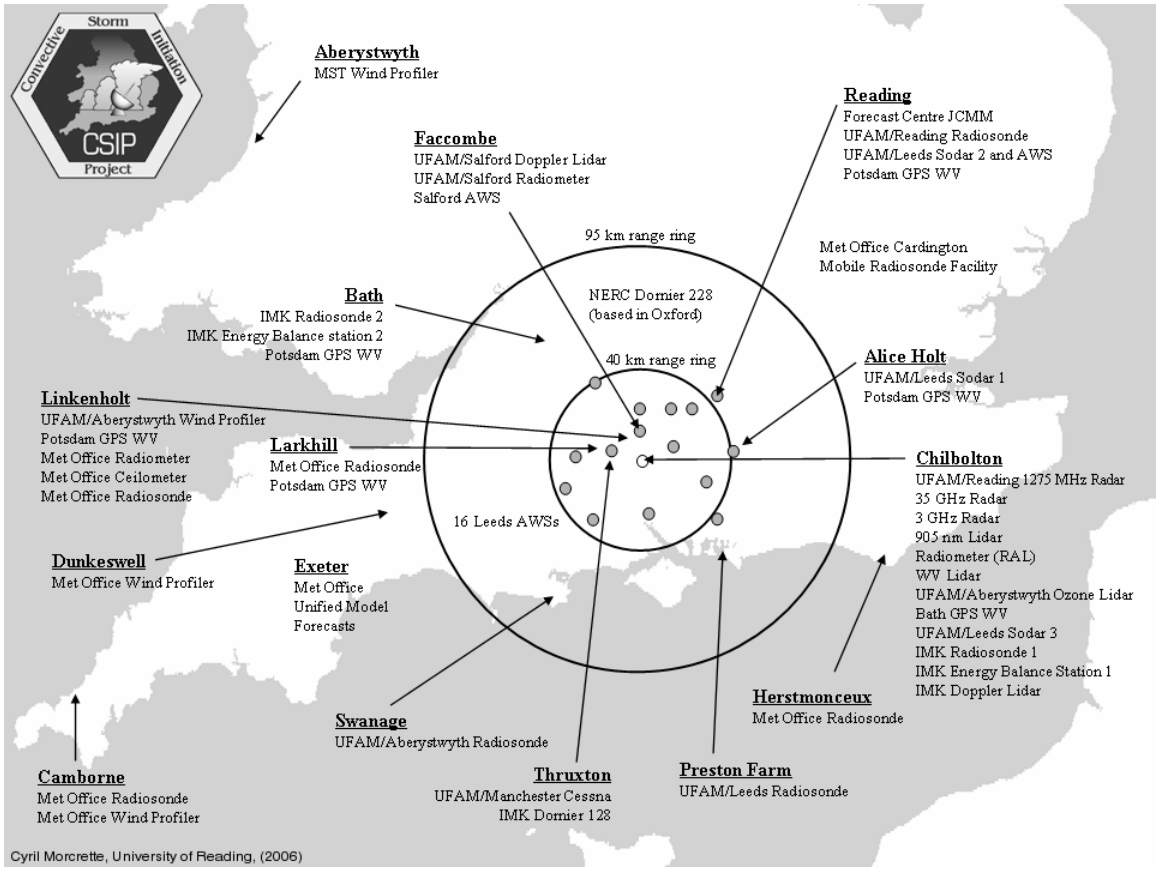


Figure 1 General overview of CSIP 2005 instruments.

   during the day with supplemental ascents every 3 hours from Camborne and Herstmonceaux and 2 hourly ascents from Larkhill.
3. A surface network of about 12 automatic weather stations all within roughly 50 km of Chilbolton.

The main campaign took place during June, July and August 2005, though a pilot study, with limited equipment, took place in July 2004. During the 2005 campaign, the UK 4 km model was quasi-operational, and it provided some guidance for operations. However, post event the 'High Resolution Trial Model' (HRTM) system was run to provide a first pass indication of performance of 4 km and 1 km models. The purpose of this document is to give a very brief overview of model performance, and, hopefully, to identify any aspects of the model which appear to show systematic error, to identify those aspects of IOPs which are of interest and a priority order for analysis. Our

primary interest is in evaluating the Unified Model and highlighting deficiencies in simulations. These deficiencies may arise from:

1. general, systematic biases in model formulation and configuration, i.e. resolution, dynamics or parametrizations,
2. specific case-dependent model errors, or
3. deficiencies in initial or boundary forcing. The latter may exist on a variety of scales.

Separating these errors is difficult, and they are, of course, related, as the accumulated impact of model error contributes to initial condition error. In this case our general way of working is to:

1. Identify gross (large scale) errors in initial conditions from available observations. This includes large scale flow, boundary layer humidity and cloud, upper level cloud, large scale forcing of ascent and regions of instability.
2. In cases where initial condition error is small, examine sensitivity to model formulation. In particular compare model and observed boundary layer development, mesoscale convergence lines, lids etc.
3. Identify and evaluate changes in model state arising from data assimilation (DA).
4. Hopefully postulate improvements to model formulation or data assimilation to improve the overall forecast agreement with observations. The modelling focus is on boundary layer development prior to triggering and influence of dynamics, turbulence and microphysics through cloud life cycle(s).The DA focus is on smaller scales compared with the large scale errors identified in 1, especially moisture, precipitation and Doppler winds.
5. Possibly iterate the above procedure once sufficient cases have provided evidence for systematic improvements.

It must be emphasised that the purpose of this document is to provide a very brief overview with recommendations for further study – a number of detailed studies will be required to get the most out of CSIP data, and any conclusions derived here must be regarded as very preliminary. While objective verification has been performed for each case, we believe that at this stage in development, subjective indications are more appropriate because of the ability to consider aspects of performance improvement beyond the overall skill of the model..

2 CSIP Cases

During the main summer 2005 campaign there were 18 Intensive Observation Periods (IOPs). Browning *et al*, 2006, summarises the IOPs. One of these was declared so retrospectively after a decision was made not to make intensive observations based on what turned out to be a poor forecast. Some of the other events turned out to have little activity of interest within the CSIP region, but, nevertheless, will not be excluded from consideration as the reasons for this lack of activity may be of interest, especially in one case which did produce intense convection and flash flooding over Yorkshire.

IOP	*Date*	*Comments*
1	15/06/2005	Triggering over SW peninsula convergence possibly modulated by upper trough.
2	19/06/2005	Yorkshire floods - no triggering in CSIP area.
3	24/06/2005	Glastonbury floods. Upper front, organised N-S lines of convection.
4	28/06/2005	
5	29/06/2005	Oxford flood - organised E-W line associated with upper level forcing or cirrus modulated surface forcing.
6	04/07/2005	Continuous stream of cells originating in NW flow over Wales, with some triggering and organisation in CSIP area.
7	07/07/2005	Showers in N flow
8	13/07/2005	Surface forced along Chilterns, S coast sea breeze, intermediate lid and little triggering
9	18/07/2005	A narrow line of convective showers associated with the passage of a surface cold front.
10	23/07/2005	Strongly suppressed convection with isolated showers initiated near outer limits of the CSIP area.
11	24/07/2005	A few shallow showers initiated in the CSIP area in a rather strongly suppressed dry slot.
12	28/07/2005	Cloud Streets from S Coast, Birmingham tornado.
13	01/08/2005	S Coast and Kent/Sussex initiation, intermediate lid with only 1 or 2 cells going deep to ~9 km. Funnel clouds over Bristol and Wiltshire.
14	11/08/2005	Retrospective IOP - no full operation. Isolated shower - possible sea breeze or upper level triggering.
15	13/08/2005	Shallow showers behind cold front.

16	18/08/2005	Weak, broadly southerly flow ahead of a band of cold-frontal rain advancing slowly from the west. Shallow showers developing later in evening.
17	19/08/2005	Scattered showers in Wales and the north-west Midlands in the north-westerly flow behind Cloud Head(s) during the early afternoon, followed by the formation of a line of showers just west of Bath.
18	25/08/2005	Westerly flow beneath upper trough - development of organised convection with strong cold pool/subsidence/gust front system.

Table 1 Summary table of summer 2005 CSIP IOPs

An informal assessment by Browning *et al, 2006,* separated the IOPs into three categories, □, □ and □. They assessed 7 IOPs to be 'α' quality and a further 6 to be 'β', the remainder being 'γ'. This assessment is based on likely value in understanding initiation rather than value for model validation, but there should be a great deal of overlap in these aims. The same informal assessment also identified likely mechanisms for convective initiation. This assessment is repeated below in Table 2. It must be emphasised that this assessment is based on a very preliminary examination of the evidence and has yet to be confirmed by more in-depth analysis. Nevertheless, it serves as a useful set of working hypotheses.

Various notable events occurred associated with CSIP IOPs, in particular flooding in Yorkshire (IOP 2), the Glastonbury Festival (IOP 3) and Oxford (IOP 5), and a tornado event (assessed as F2 on the Fujita scale) in Birmingham (IOP 12) and funnel clouds observed over Bristol and Wiltshire (IOP13).

Phenomena / IOP	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Rating	α	γ	β	γ	α	α	β	α	α	γ	β	α	β	β	γ	β	β	α
Primary initiation (in area)	Y				Y	Y				Y	Y	Y	Y	Y		Y	Y	Y
Secondary initiation (in area)						(Y)	Y					Y	Y				Y	Y
Intense showers	Y		Y		Y	Y	Y		Y			Y	Y	Y			Y	Y
Upper-level forcing	Y				Y	Y	Y		Y		Y	Y		Y	Y			Y
Hill effects					Y	Y		Y			Y	Y	Y			Y		
Coastal effects	Y							Y			Y		Y	Y				
Mesoscale low-level convergence	Y							Y	Y	Y		Y	Y	Y		Y		Y
Cloud shadowing					Y					Y						Y	Y	
Multiple lids	Y		Y		Y			Y				Y						
Main lid height varies	Y								Y							Y		
Highly organised showers			Y		Y		Y		Y			Y	Y		Y			Y

Table 2 Preliminary assessment of relevant mechanisms leading to convection initiation within the CSIP area - from Browning *et al*, 2006. Entries in parentheses are additions by the current authors. Also shown are overall assessments of IOP rating.

3 The Model System

Most of the runs described here were performed using versions of the 'High Resolution Trial Model' (HRTM) Unified Model Suite (version 5.1.5). This is based on UM 6.0 and comprises a 1 km model nested in a 4 km model nested in the 12 km UK mesoscale domain. The 1 km model has 76 levels, the other two domains 38. The domains are shown in Figure 2. Runs discussed here are 'spin-up' runs, i.e. using low resolution initial data from the 12 km model. Either the 0000 or 0600 UTC runs have been used (starting from the T+1 operational dump). Results from data assimilation trials will be presented in the future, but current experience suggests that beyond T+6 spin-up runs give a good indication of model performance. The 12 km model configuration was as the operational mesoscale model at the time. The 4 km was similar to the quasi-operational 4 km model, the main difference from the 12 km being a modified convection scheme which greatly restricts the mass flux, so that the scheme mainly deals with shallow convection, and deep convection develops explicitly. This scale of explicit convection is controlled by fixed horizontal ∇^4 diffusion. Both 12 and 4 km models had the standard G3 set of 38 levels. The 1 km model runs without any convection scheme and similar ∇^4 diffusion. It has a doubled set of 76 levels, with every alternate level corresponding to a level in the 4 km model. Both 4 km and 1 km models have been run with rain as a prognostic variable in addition to ice and cloud.

4 Classification of IOPs

We shall now endeavour to divide the IOPs into categories likely to provide information about specific processes in the model system, including data assimilation. This classification is based, in part, on Table 2.

4.1 Model Formulation and Parametrizations

Interests lie in how well the model generates primary initiation, subsequent evolution of convection, secondary initiation and organisation. We shall concentrate, at least initially, on primary initiation within the boundary layer. We need to be confident we can properly model this before attacking mid-level triggering.

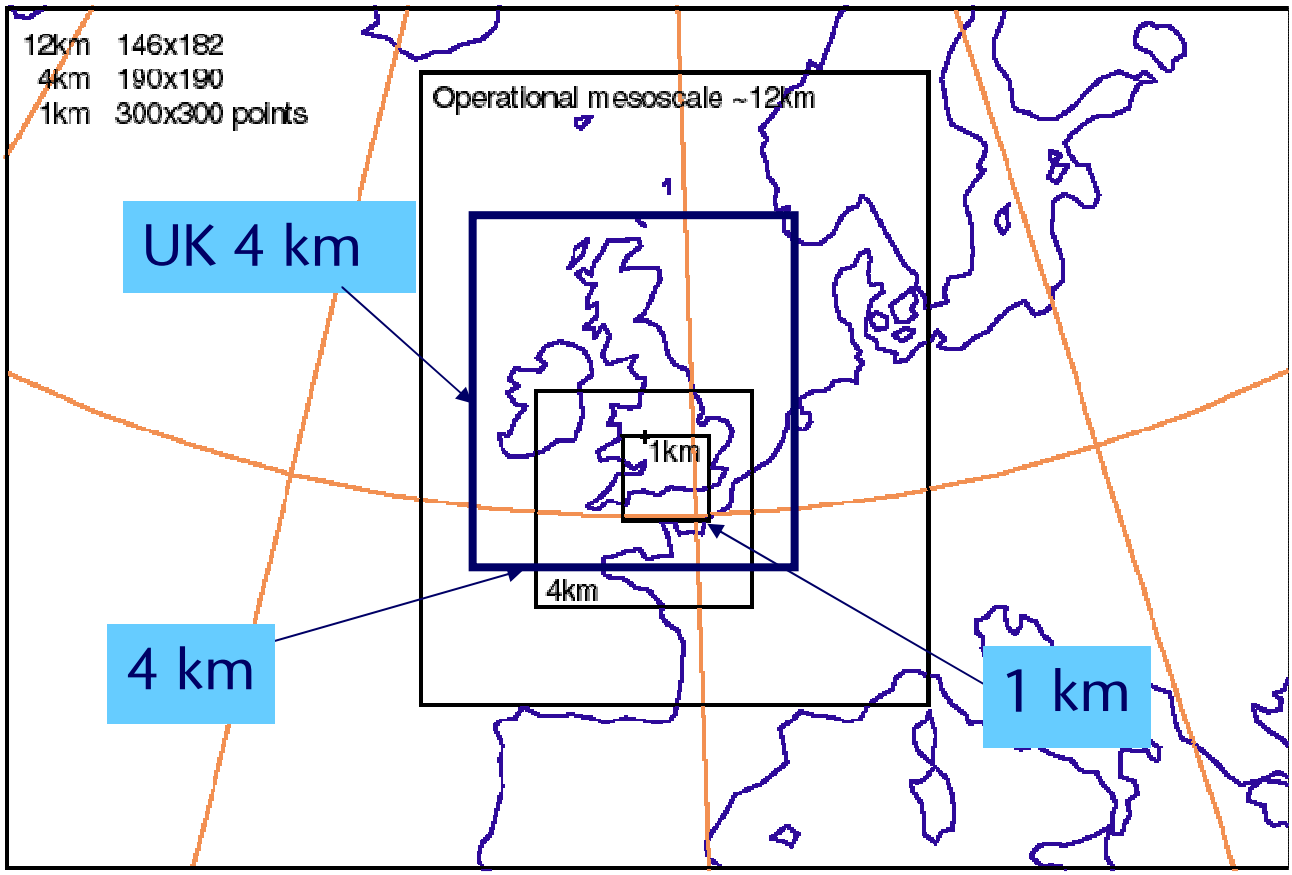


Figure 2 HRTM Domains

Primary Initiation in the Boundary Layer

The behaviour of the boundary layer/turbulence scheme is central. Gross errors are likely to be:

- Large scale flow (e.g. too strong a mean flow).
- Boundary layer humidity and any resulting cloud (probably influenced strongly by soil moisture, but also influenced by large scale errors and sea/land transitions),
- Free tropospheric cloud influencing surface energy budget.
- Large scale forcing of ascent.
- Distribution of instability and strength of any stable layers ('lids').

The role of the boundary layer in developing convection is, first, the development of heterogeneity producing preferred triggering at a particular place and time, and, second, the condensation (and mixing) response to produce dynamical instability that grows. It is likely that formulation errors, at a given resolution contribute to errors in both these processes. Heterogeneity typically exists on two distinct scales. Mesoscale variability exists resulting from orography, land/sea contrast, land-use variability, and variations in surface heating due to cloud or soil conditions, as well as internal mesoscale dynamics. Microscale variability exists, possibly for related reasons, but also due to instabilities in the flow. Mesoscale variability is often associated with convergence lines in the low level flow. Cloud streets are a related mesoscale phenomenon which may (or may not) be tied to surface features.

Our primary aim, therefore, is to make detailed comparisons between modelled and observed time history of boundary layer development up to primary initiation. Our definition of 'boundary layer' includes development all the way through to first shower initiation, and so encompasses breaking through multiple 'lids'. This analysis will include:

- the mechanisms behind mesoscale features such as convergence lines, moist regions, or lids
- area-average behaviour such as boundary layer depth, moistening etc.
- if possible, some idea of the development of large microscale variations in BL structure from Acrobat, AWS and Cessna date will be used to identify deficiencies in the model.

In the long run, we hope to experiment with stochastic modifications to our turbulence schemes, and information on large microscale variations will be extremely important.

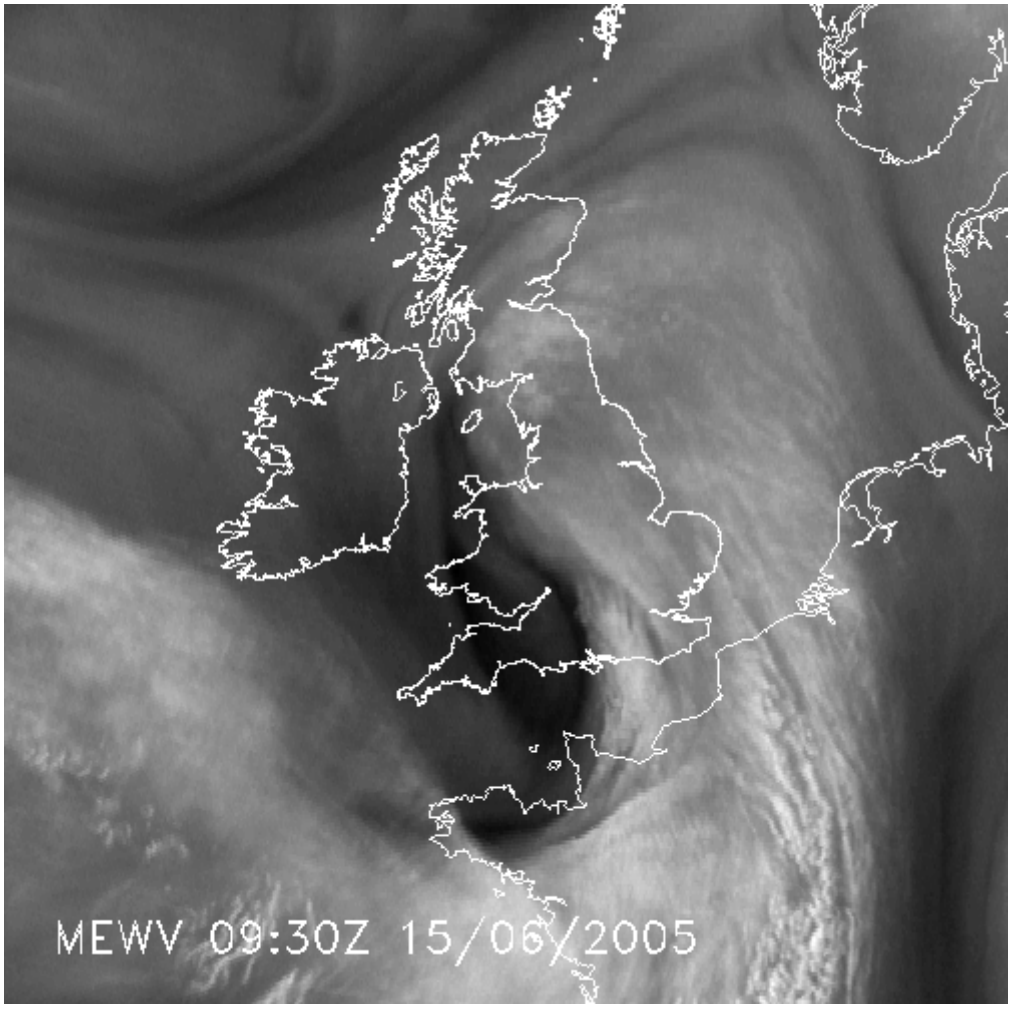


Figure 3 Contrast-enhanced water vapour image from Meteosat Second Generation at 0930 UTC, 15/06/2006 IOP 1

IOPs of interest are all those with a good record of boundary layer development up to initiation (or near initiation). A number of IOPs include primary initiation or coastal/hill effects indicating strong surface forcing Of these, IOPs 1, 5, 8 and 12 are classified α and IOPs 13, 14R, 16 and 17 are classified β. IOP 2 may also be worth studying as an intense false alarm occurred close to the area.

4.1.1.1 IOP 1

A single, long lived cluster of showers triggered around 0915 UTC along what appears to be a SW Peninsula convergence line. Imagery suggests other regions of weak triggering along this line, perhaps modulated by orography or orographic waves, but only one area intensified. The area that intensified was directly beneath the centre of the upper level potential vorticity (PV) anomaly which forced the system, and its motion was roughly synchronised with the motion of the PV anomaly. Figure 3 shows water vapour imagery which clearly indicates the dark (dry) zone which is well correlated with upper level PV. Figure 4 shows a summary of imagery shortly after triggering – the circle is centred on Chilbolton with range rings at 25, 50, 75 and 100 km, and the azimuth of Chilbolton Range-Height Indicator (RHI) scans are marked. The shower of interest is located just north of the 255° azimuth at 90-100 km range. There is a hint of a wave pattern in the cloud top height with ~ 30 km wavelength running along the SW Peninsula (and main wind direction).

The overall evolution of model forecasts is remarkably good on this occasion. The frontal clearance was almost in the right location, though the frontal precipitation was a little strong and less broken up than the radar imagery. Triggering occurred a little early in both 4 km and 1 km models, with the first sign of precipitation at about 0815 UTC. This occurred along a line close to the observed cloud line in which triggering occurred. In the 1 km, showers occurred all along this line (~ 50 km) rather than in one place, though the strongest cell went on to develop at the expense of the others. This is illustrated in Figure 5, which shows the 1 km model triggering along a line starting at but extending to the east of the actual cell. This develops into a number of intense cells (Figure 6) and eventually one organised cluster (Figure 7). The low level convergence line at 0900 UTC is shown in Figure 8.

It is evident from the Figures that:

1. The 1 km model produces a fairly realistic shower cluster but also far too many small precipitating cells, especially behind the main system.
2. The cluster in the 1 km model propagates too fast.
3. The 4 km model produces a remarkably good forecast, without the additional cells of the 1 km model, and better located later in the forecast.
4. Although the evolution is unsteady, even the 12 km model produces parametrized showers in the right place (if too widespread and intense), which suggests that the intensification of this cluster is driven by large scale features of the flow.
5. The forcing for ascent is usually ahead of a PV anomaly, not directly below it, which suggests that, in this

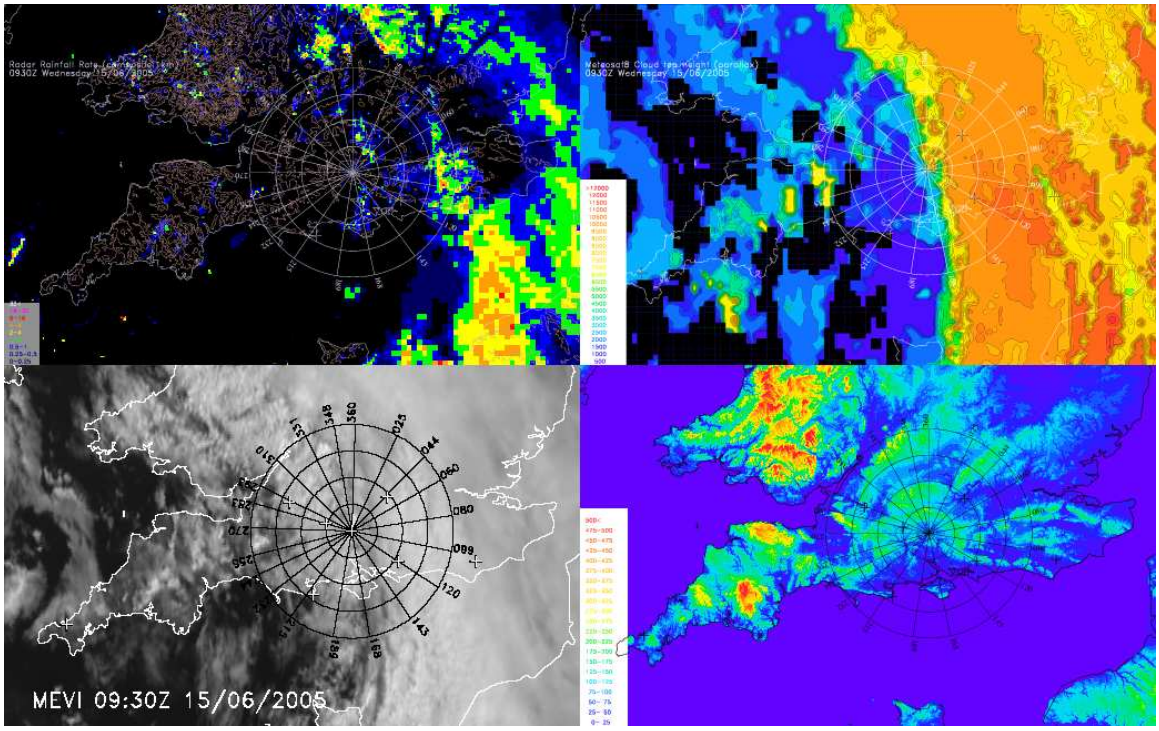


Figure 4 Imagery shortly after shower initiation in IOP 1 at 0930 UTC 15/06/2005. 1/2/5 km radar composite (top left), MSG cloud top height (top right), MSG high resolution visible (bottom left) and orography (bottom right).

case, the upper tropospheric cold pool is a dominant factor in generating instability rather than large-scale ascent ahead of it.

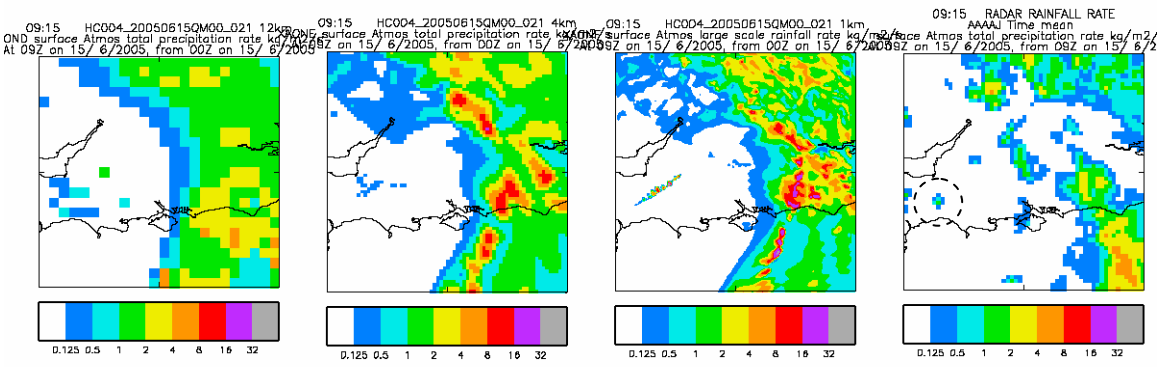


Figure 5 IOP 1 model forecasts of precipitation rate from (left to right) 12 km, 4 km and 1 km models at 0915 UTC from 00 UTC initial conditions, compared with 5 km radar composite (right). The shower of interest is circled in the radar image.

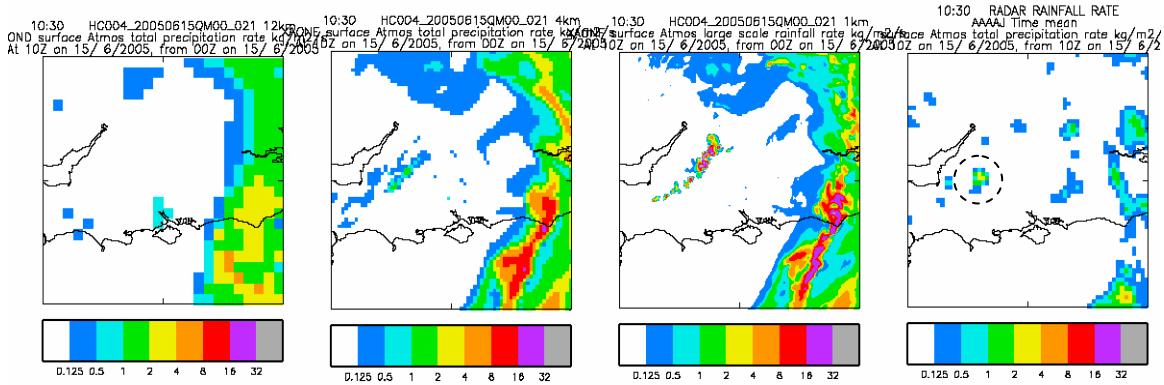


Figure 6 IOP 1 model forecasts of precipitation rate from (left to right) 12 km, 4 km and 1 km models at 1030 UTC from 00 UTC initial conditions, compared with 5 km radar composite (right). The shower of interest is circled in the radar image.

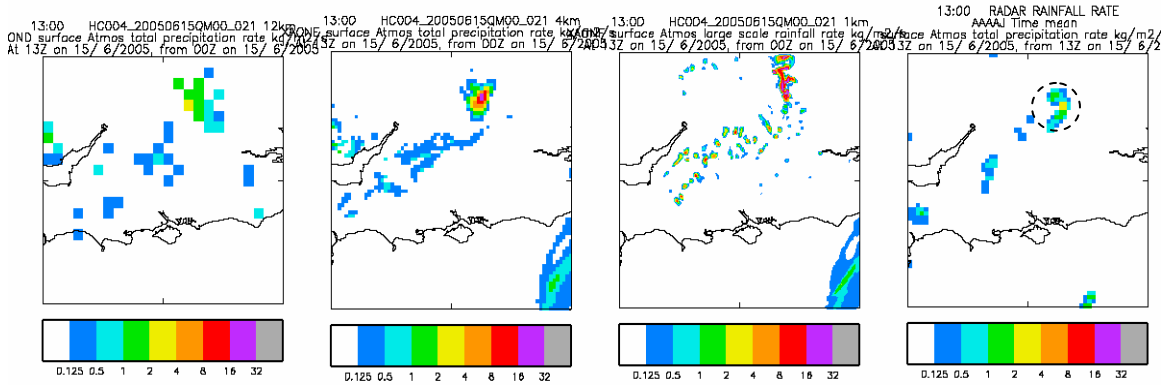


Figure 7 IOP 1 model forecasts of precipitation rate from (left to right) 12 km, 4 km and 1 km models at 1300 UTC from 00 UTC initial conditions, compared with 5 km radar composite (right). The shower of interest is circled in the radar image.

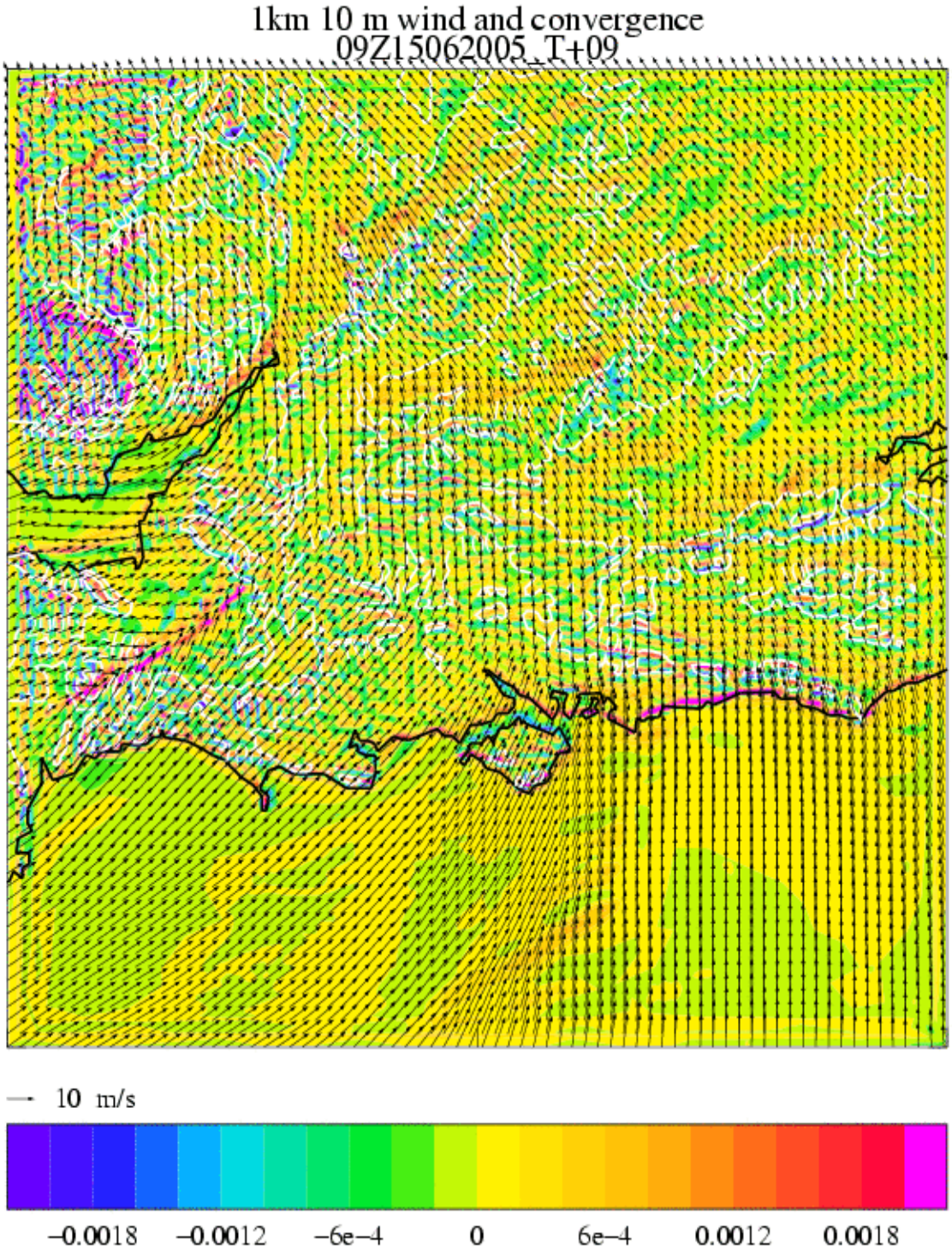


Figure 8 Forecast 10 m windfield and divergence in 1 km model at 0900 UTC, 15/06/2005, IOP 1, showing convergence line to the west of the domain.

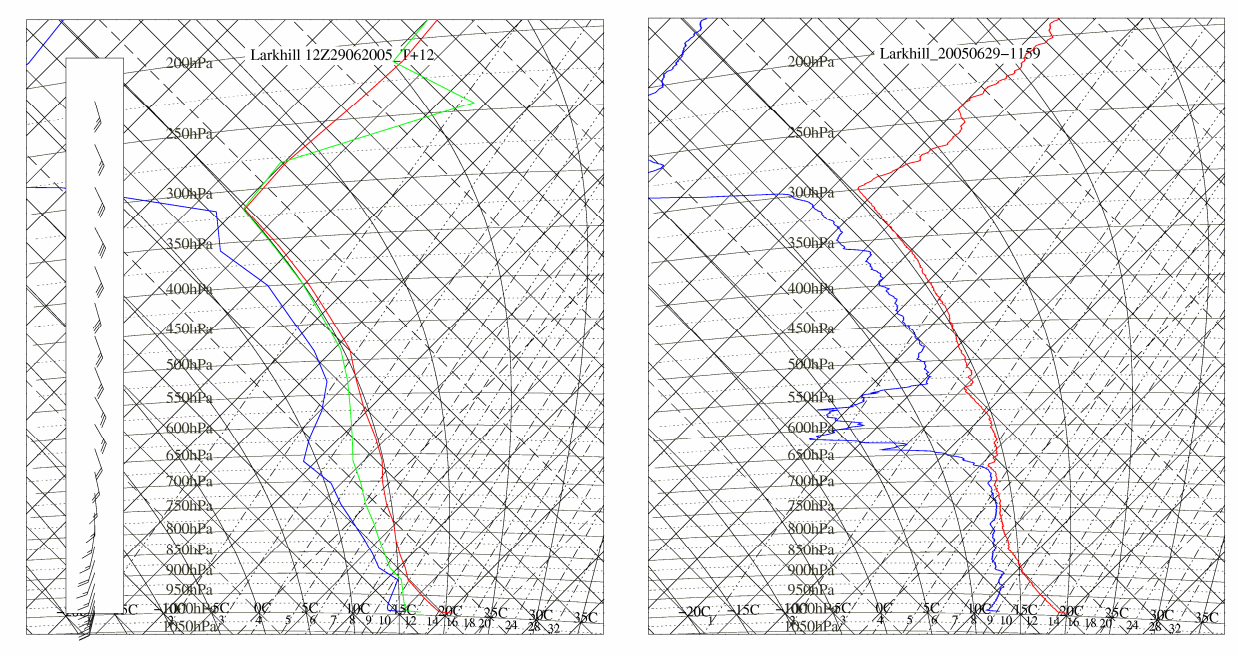


Figure 9 Tephigram showing Larkhill ascent launched 1159 UTC 29/06/2005 (right) compared with operational mesoscale (12 km) T+12 forecast from the 0000 UTC run (left)

4.1.1.2 IOP 5

The primary forcing for instability arose from upper level forcing associated with an upper level vortex visible in both the 12 km model and water vapour imagery. Thunderstorms triggered along a spiral arm associated with this vortex, to the east of its centre, with first showers forming over the SW Peninsula. However, the precise location of triggering in the CSIP area appears to have been heavily modulated by cloud shadowing arising from old, 'orphaned' anvils from previous deep convection over France, perhaps modulated by orography. If this is true, it is very unlikely that the model has these anvils in the right place and time, not least as the initial state comes from the 12 km model with parametrized convection. The Moisture Observation Processing System (MOPS) may have introduced some useful, information, so this case may prove a useful test of MOPS.

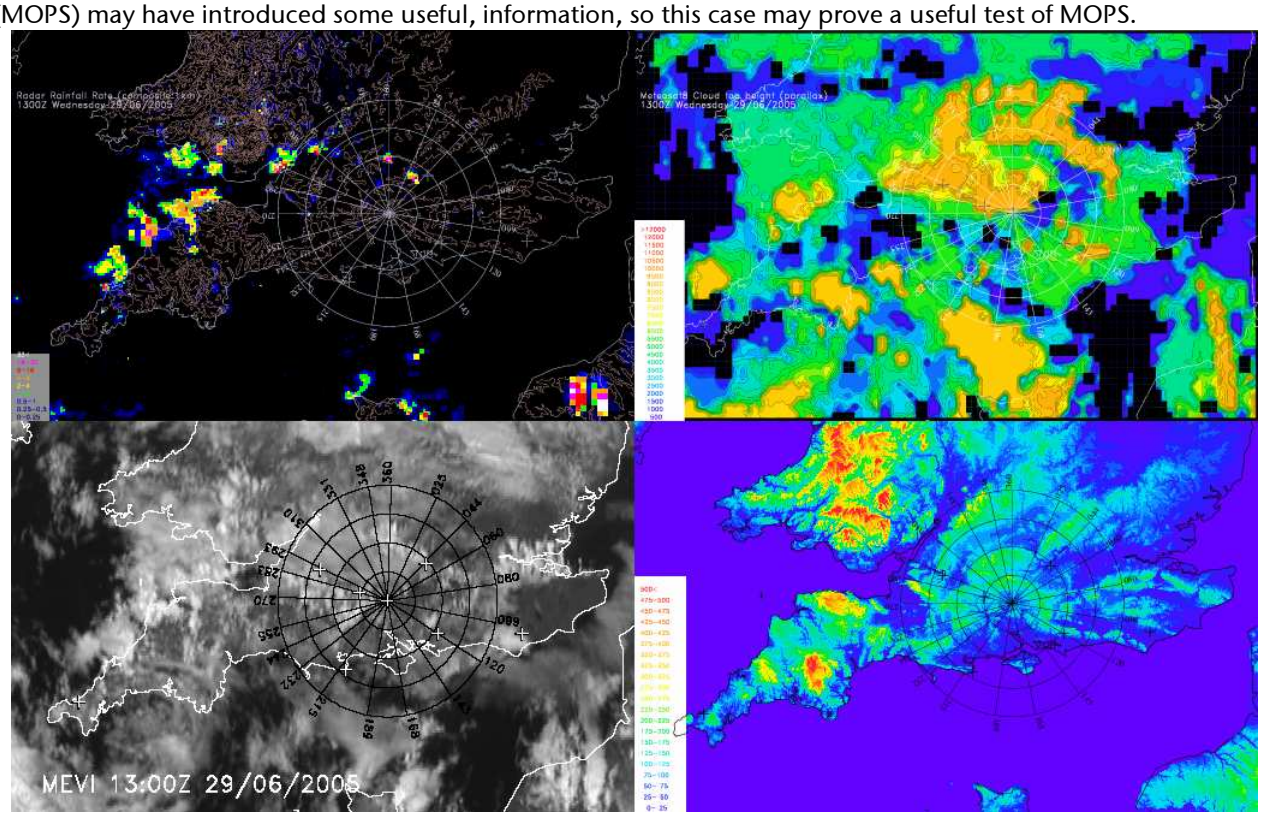


Figure 10 Imagery shortly after shower initiation in IOP 5 at 1300 UTC 29/06/2005. 1/2/5 km radar composite (top left), MSG cloud top height (top right), MSG high resolution visible (bottom left) and orography (bottom right).

Figure 10 shows an indication of high cloud at 1300 UTC (orange colours in the cloud top height image). While not conclusive from this image, careful examination of the sequence of images suggests that the first showers form in the areas not shadowed by this high cloud. One might be surprised that the cloud has such an impact as it appears relatively tenuous on imagery. However, the sounding from Larkhill released at 1159 UTC (Figure 9) shows a moist upper layer which extends from 540 hPa up to the tropopause at 300 hPa. This layer seems to be captured in the mesoscale model forecast (if anything, it is the cloud below 650 hPa which is reduced or absent and the dry layer between greatly underdone). In contrast, the models do not show the heterogeneity of upper level cloud evident in Figure 10.

The line of showers eventually developed into a fairly intense line of thunderstorms which drifted north (Figure 11). The storms that passed over Oxford lead to localised flooding. Also of note are the cloud streets over central southern England which formed in the strong southerly flow. Examination of the model cloud suggests that the old anvils observed are absent (or, at least, in different places).

In this case, the HRTM performed reasonably well to the extent that a clear line of showers formed with the right orientation in roughly the right place. However, triggering is all along the line, somewhat early and there is little suggestion of suppression in some areas, which is consistent with the upper cloud distribution, though by no means proof of causality. The first sign of triggering on radar in the CSIP region is around 1215 UTC. By this time, convection in the model is already well developed, having triggered around 11 UTC (Figure 13). By 1400 UTC, the 1 km model has a contiguous line of well-developed, intense showers. In addition there is clear indication of spurious weak precipitation along cloud streets originating on the south coast and tracking north. Cloud streets are evident at various times in imagery, a good example being at 1500 UTC (Figure 11), but also at earlier times, but at no time was significant precipitation associated with them. Rather, they form precursors upwind of deeper cells.

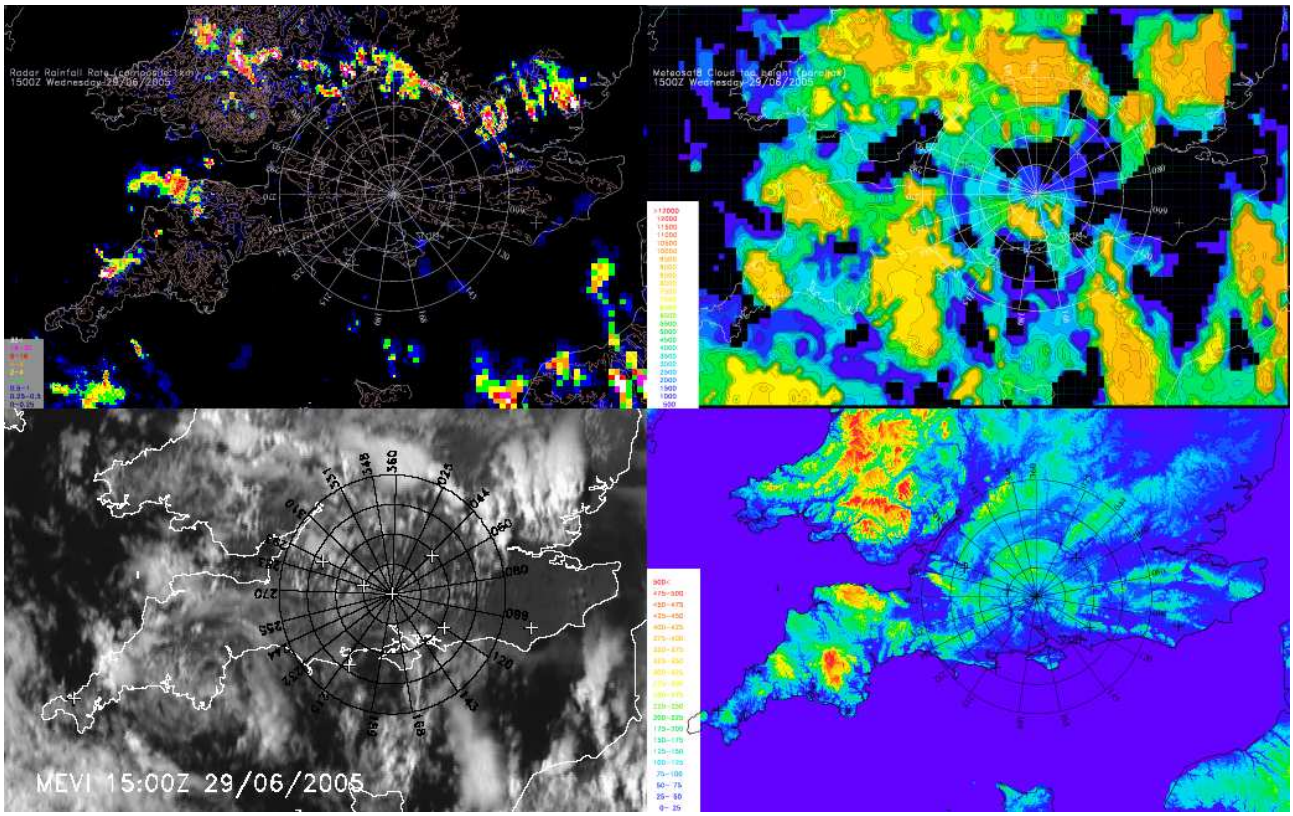


Figure 11 Imagery shortly after shower initiation in IOP 5 at 1500 UTC 29/06/2005. 1/2/5 km radar composite (top left), MSG cloud top height (top right), MSG high resolution visible (bottom left) and orography (bottom right).

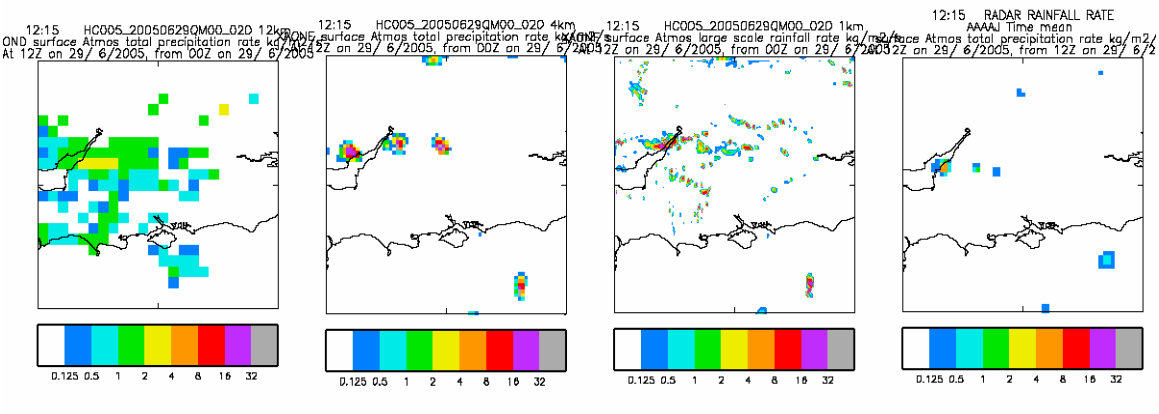


Figure 13 IOP 5 model forecasts of precipitation rate from (left to right) 12 km, 4 km and 1 km models at 1215 UTC from 00 UTC initial conditions, compared with 5 km radar composite (right).

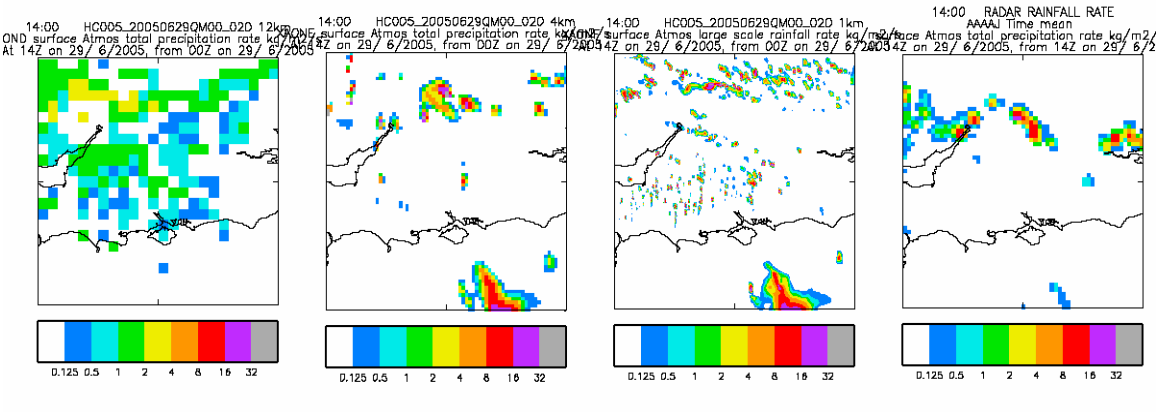


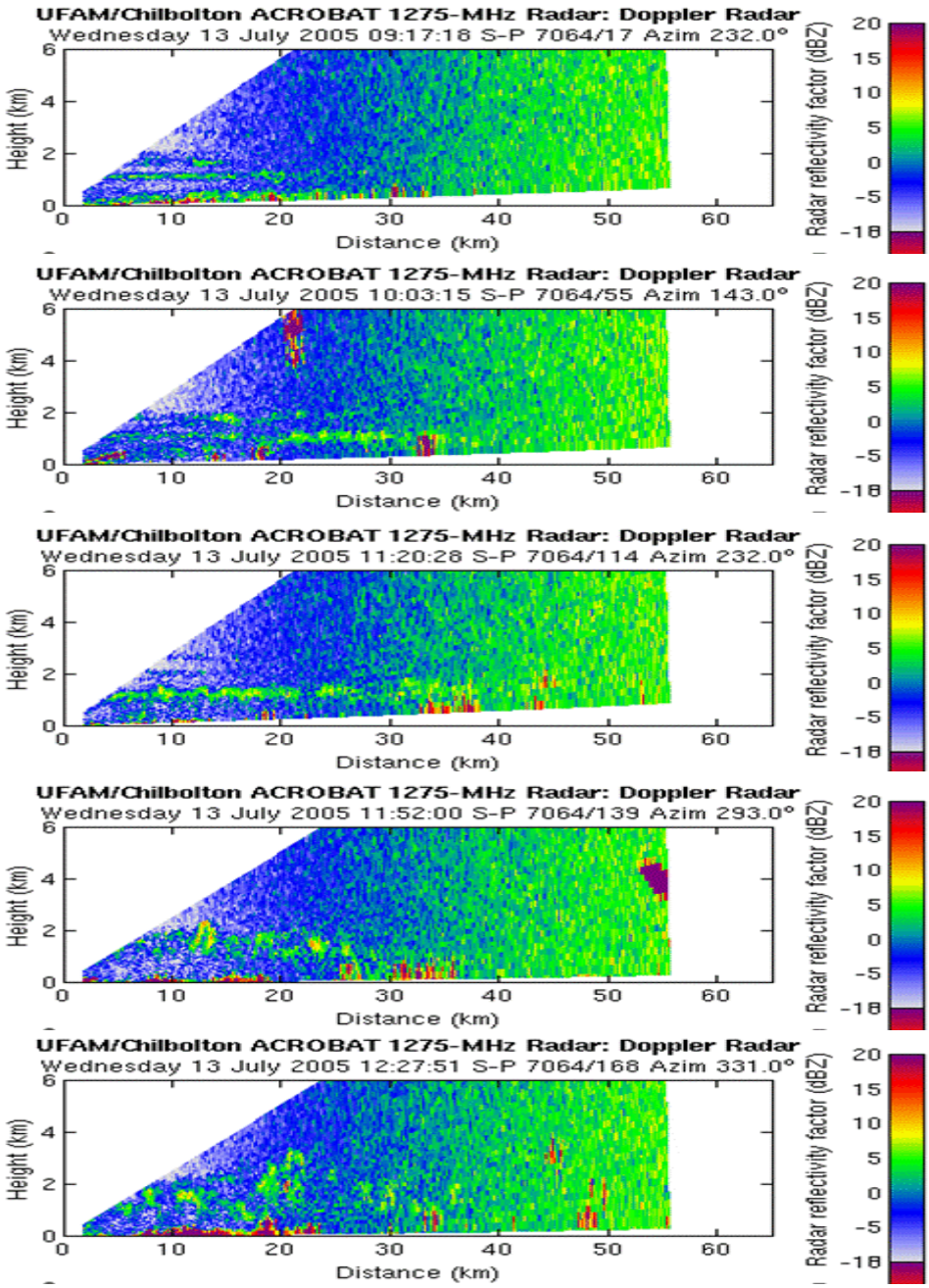
Figure 12 IOP 5 model forecasts of precipitation rate from (left to right) 12 km, 4 km and 1 km models at 1400 UTC from 00 UTC initial conditions, compared with 5 km radar composite (right).

The 4 km model actually appears to do better in this case, because initiation is suppressed. This has the effect of removing the small scale precipitation, and also holding back the line development which is then better located. It is interesting to note that the 12 km (parametrized) convection shows a hint of the linear structure, but also triggers more weakly in the 'cloud street' region.

4.1.1.3 IOP 8

IOP 8 was weakly forced synoptically, with a weak NNW flow associated with a ridge extending across the central UK . Surface forcing dominated resulting in a relatively straightforward diurnal cycle of convective boundary layer followed by cumulus development. A sea breeze formed along the south coast and progressed inland during the afternoon, eventually reaching Chilbolton. This cooler onshore flow was well observed and cut off cumulus activity.

Figure 14 shows a selection of 'clear air' RHI scans from the ACROBAT radar. These show the presence of multiple stable layers in the early stages, followed by convective boundary layer growth and, eventually, penetrative cumulus convection. These data should, in combination with high time frequency soundings, allow a detailed evaluation of the development of the boundary layer during the day. Perhaps the main outstanding question of the IOP is why very few showers actually occurred. The operational mesoscale model forecast widespread



showers over much of the area, and this message was repeated by the 1 km model.

Figure 14 Radar reflectivity from selected RHI scans from 'clear air' 1250 MHz radar during IOP 8

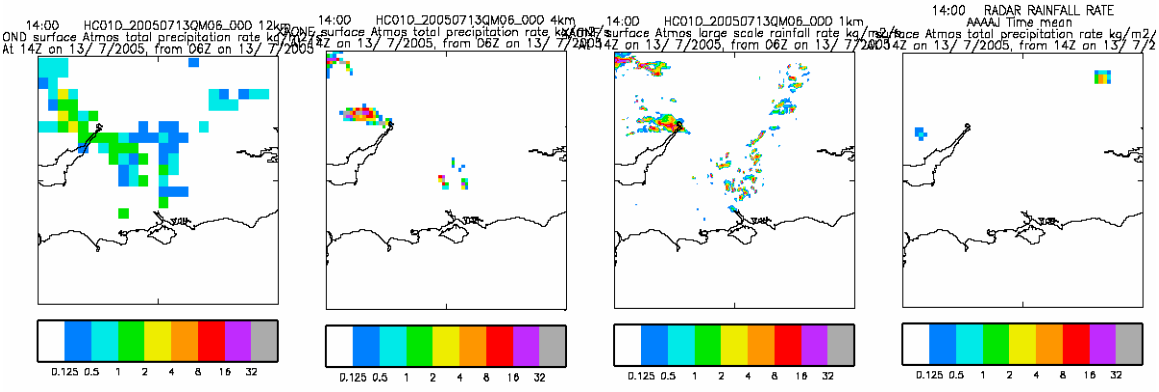


Figure 15 IOP 8 model forecasts of precipitation rate from (left to right) 12 km, 4 km and 1 km models at 1400 UTC from 0600 UTC initial conditions, compared with 5 km radar composite (right).

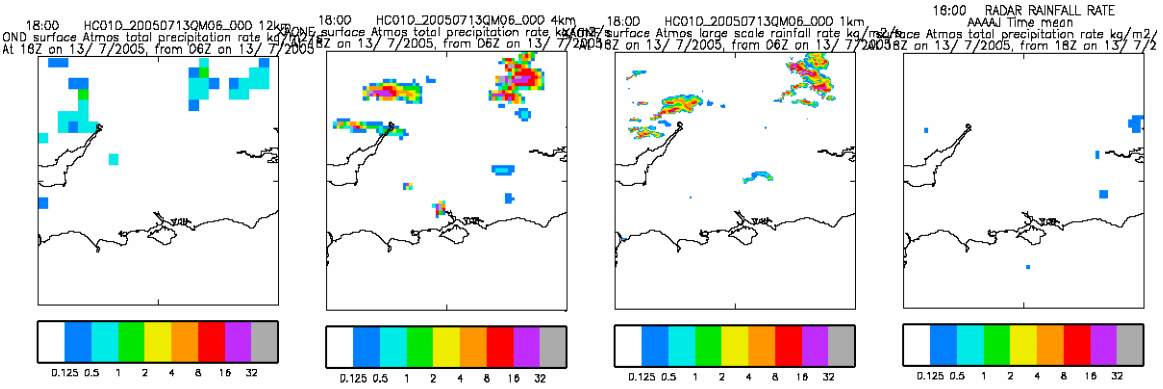


Figure 16 IOP 8 model forecasts of precipitation rate from (left to right) 12 km, 4 km and 1 km models at 1800 UTC from 0600 UTC initial conditions, compared with 5 km radar composite (right).

The 0000 UTC run of the 12 km mesoscale model shows a region of moderate CAPE (~600 J/kg, based on parcel ascent from 950 hPa) and no CIN at 1500 UTC consistent with the model's convection distribution (Figure 17). This is associated with a tongue of high θ_w air crossing the country. The high resolution models follow this area of CAPE and trigger numerous precipitating cells. Imagery shows development of convection in this area, and the ACROBAT data above confirms cumulus activity. However, very little precipitation was observed early in the afternoon, with only a few cells to the NE of the CSIP area (Figure 15). The models went on to develop quite intense showers in this area (Figure 16), though by this time the actual showers had drifted further into East Anglia.

Possible explanations for the excessive activity in all models may involve inhibition of precipitation formation by microphysics, as high levels of aerosol were observed by the lidar system, and/or inhibition by the multiple 'lids' evident in Figure 14 which were not captured by the model.

Shower activity was cut off from the south coast by a sea breeze which eventually reached Chilbolton in the late evening. This appears to have been captured by the high resolution models, though somewhat disrupted by the spurious showers. More in-depth comparison is warranted.

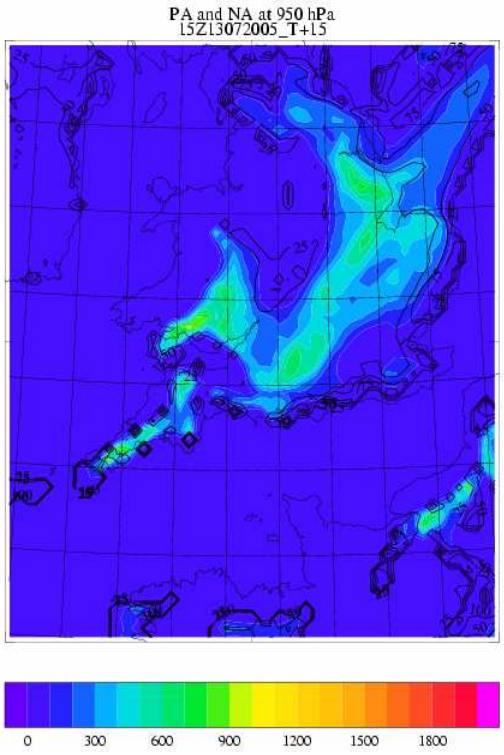


Figure 17 950 hPa CAPE at 1500 UTC from 0000 UTC 12 km mesoscale model forecast.

4.1.1.4 IOP 12

IOP 12 was notable for the intense thunderstorms which developed along a frontal zone. At least one of these storms produced a tornado over Birmingham which was unusually strong for the UK and produced significant structural damage. The region of this storm was close to the 'triple point' between warm, cold and occluded fronts associated with a developing cyclone (Figure 19).

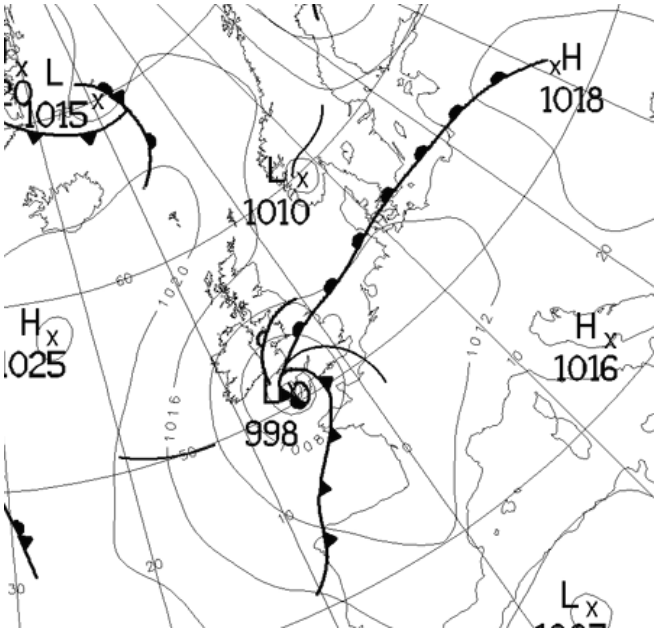


Figure 19 Synoptic analysis at 1200 UTC 28/07/2005

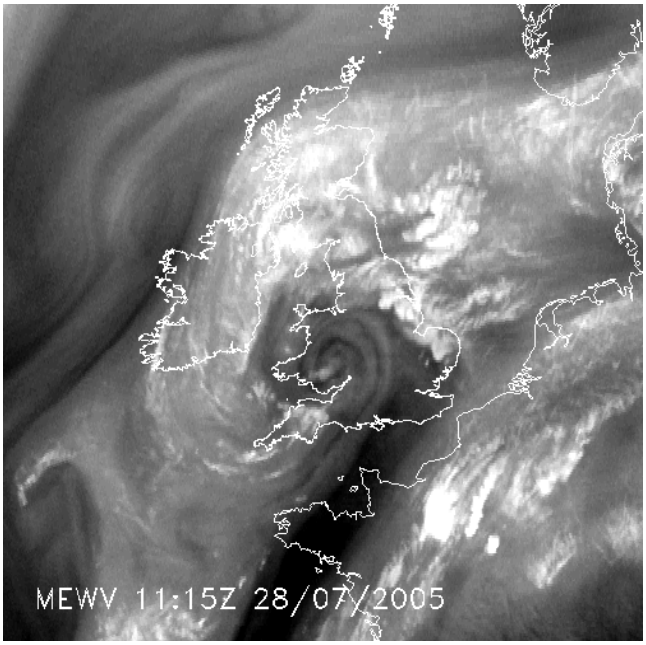


Figure 18 Enhanced MSG water vapour image at 1115 UTC, 28/07/2005

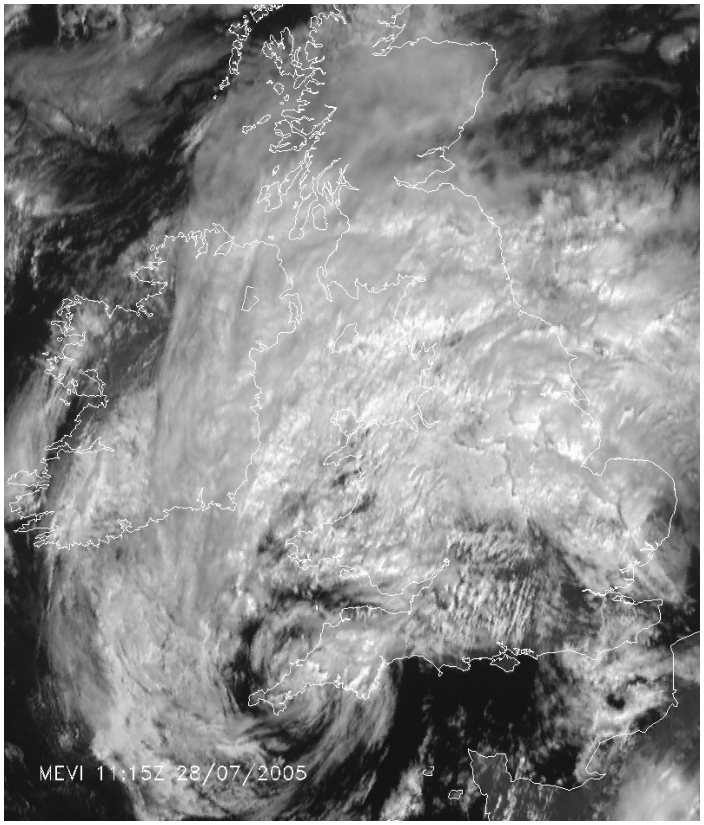


Figure 20 MSG high resolution visible image at 1115 UTC, 28/07/2005

The mechanism for initiation is of interest in this case as it was associated with the formation of very distinct cloud streets in the strong southerly flow beneath the dry intrusion of the cyclone. The dry intrusion is illustrated using water vapour imagery in Figure 18. Corresponding visible imagery is shown in Figure 20. Figure 21 shows data from the same time in the CSIP area, and shows well-organised cloud streets with stronger development to the west, with some young showers to the NW of Chilbolton. The regular periodicity of the cloud streets is evident in

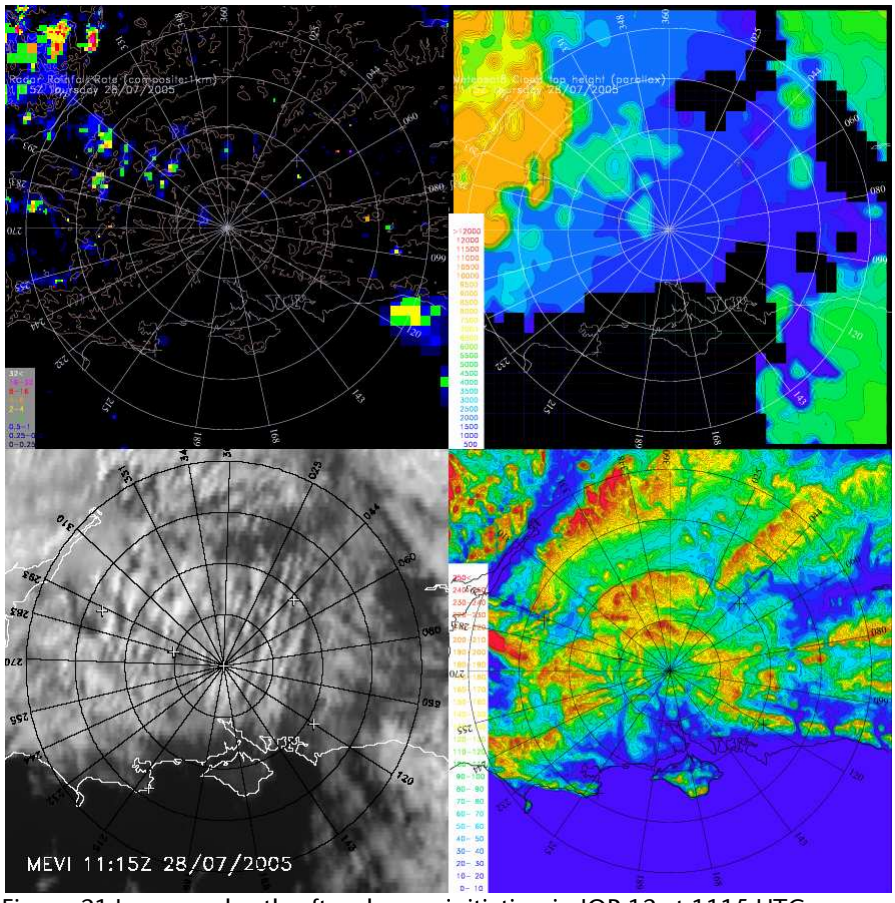


Figure 21 Imagery shortly after shower initiation in IOP 12 at 1115 UTC 28/07/2005. 1/2/5 km radar composite (top left), MSG cloud top height (top right), MSG high resolution visible (bottom left) and orography (bottom right). Note cloud streets in visible image.

this radar image.

The wavelength of these cloud streets changed with time, presumably as the depth of the boundary layer increased. They resemble those observed in IOP 8 but it is notable that on this occasion they did trigger deep clouds within the CSIP domain. We anticipate a substantial amount of useful information to be derivable from the Chilbolton scans. It is also interesting to note that the water vapour imagery (Figure 18) shows small-scale banding in the dry intrusion. These wrap around the low centre, but are fairly straight and aligned roughly with the low-level cloud streets (and the mean flow) over Chilbolton.

The 1 km model also developed cloud streets which went on to form deep precipitating clouds. These are well illustrated by Figure 22, at 1200 UTC. This shows a representation of cloud based on outgoing long-wave radiation. The streets look remarkably realistic. However, initial impressions suggest that they break up into large, distinct cells too soon (along their track) and become relatively disorganised. The wavelength of the streets may also be too large. Nevertheless, this is a remarkably good simulation. This figure also shows less organised clouds in a band stretching from the Thames estuary to the NW and deep clouds eventually developing to the NW.. This band corresponds to the frontal region The double line of showers over London is advected in from outside the region. The early stages of these simulated streets give rise to spurious precipitation clearly associated with the simulated streets (see Figure 24, which may be compared with Figure 23, and enlarged segment of Figure 20.

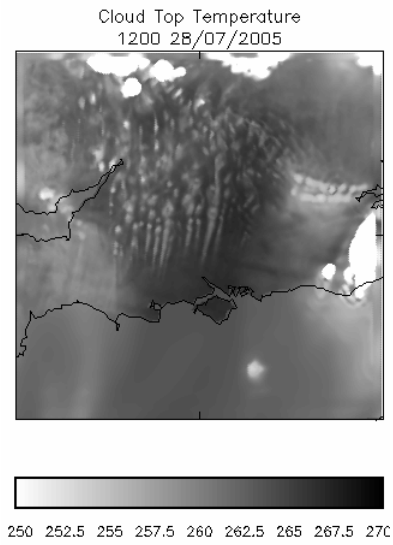


Figure 22 1200 UTC forecast of radiance temperature of outgoing broadband long-wave radiation from 0600 UTC run of 1 km model, IOP 12.

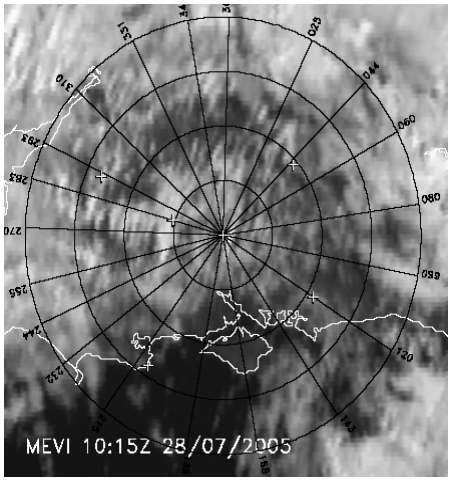


Figure 23 MSG high resolution visible image at 1015 UTC from IOP 12.

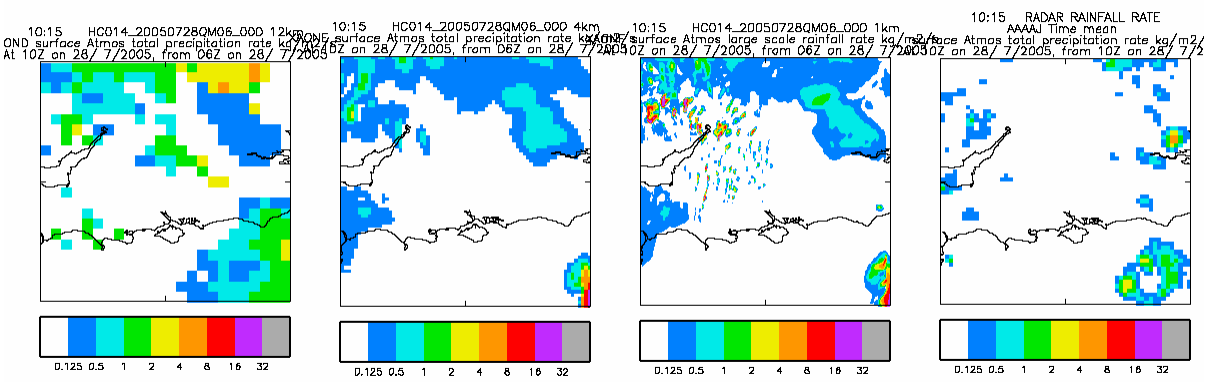


Figure 24 IOP 12 model forecasts of precipitation rate from (left to right) 12 km, 4 km and 1 km models at 1015 UTC from 06 UTC initial conditions, compared with 5 km radar composite (right).

4.1.1.5 IOP 13

IOP 13 was unusual in that convection appears to have initiated overnight overland, primarily over Kent, Sussex and London, before spreading into the CSIP region, possibly via the development of sea breezes. Though primary initiation probably occurred in the region, it may well have been influenced by prior convection outside and may prove complex to analyse.

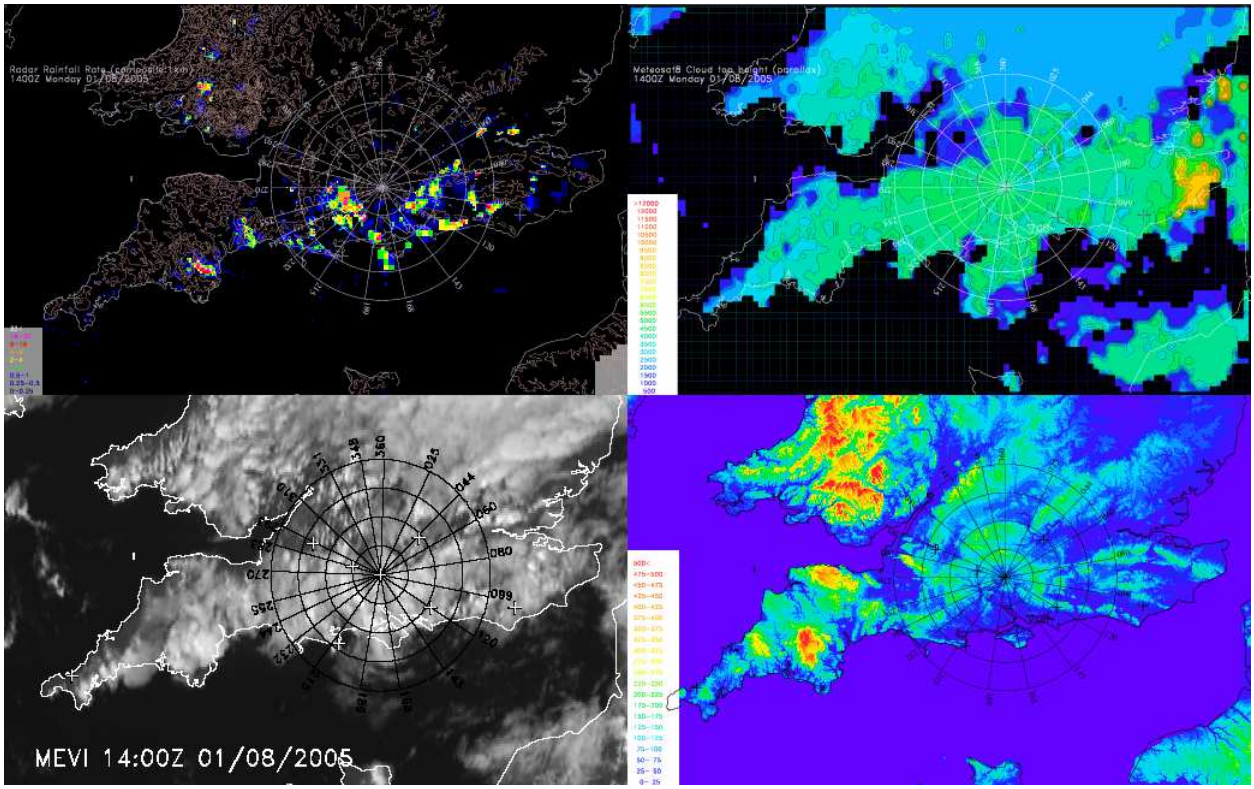


Figure 25 Imagery during IOP 13 at 1400 UTC 01/08/2005. 1/2/5 km radar composite (top left), MSG cloud top height (top right), MSG high resolution visible (bottom left) and orography (bottom right).

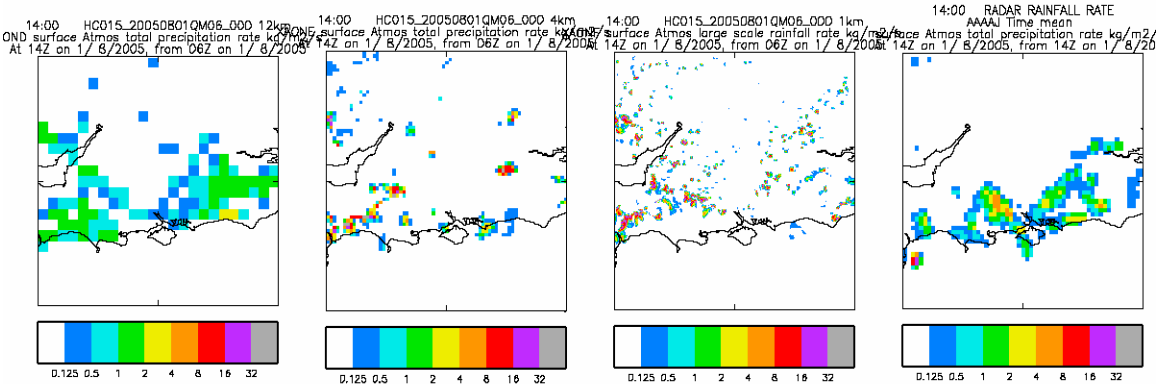


Figure 26 IOP 13 model forecasts of precipitation rate from (left to right) 12 km, 4 km and 1 km models at 1400 UTC from 06 UTC initial conditions, compared with 5 km radar composite (right).

The 1 km model performed qualitatively well, though once more produced too much small scale precipitation (Figure 26). The 4 km model showed its usual characteristic of too few, too large cells but otherwise performed reasonably. There is a hint of excessive inland progression of the showers later in the day, but the reasons for this may be difficult to untangle. There should be good statistical information about cloud depth and microphysics for comparison with the models, and this may be the most fruitful use of this case. Later in the day, Chilbolton RHIs showed some clouds deepening to tropopause level, while most had been confined by a lower lid. The mechanism for this is of interest, as well as the simple question of whether the models have the same distribution.

4.1.1.6 IOP 14R

IOP 14 was declared retrospectively, as operational forecasts had lead to the expectation of a strong lid inhibiting convection. In the event an isolated shower triggered close to Chilbolton at around 1635 UTC. Later cells developed from this which may represent a splitting of the storm. However, only limited CSIP observations are available. It therefore is difficult to identify major errors in model simulations.

4.1.1.7 IOP 16

The main features of interest in IOP 16 were:

- the early development of cumulus closely coupled to orography,
- the influence of cirrus on surface heating, suppressing convection,
- a mesoscale 'Area of Deep Convection' (ADC), suggested by an elevated boundary-layer top observed by the 3 GHz radar,
- well-observed deepening of convection as time progressed.

Figure 27 shows the developed cumulus to the east of the approaching cirrus sheet. Though not obvious from this image, Chilbolton RHIs clear show the suppression of convection as the cirrus approaches.

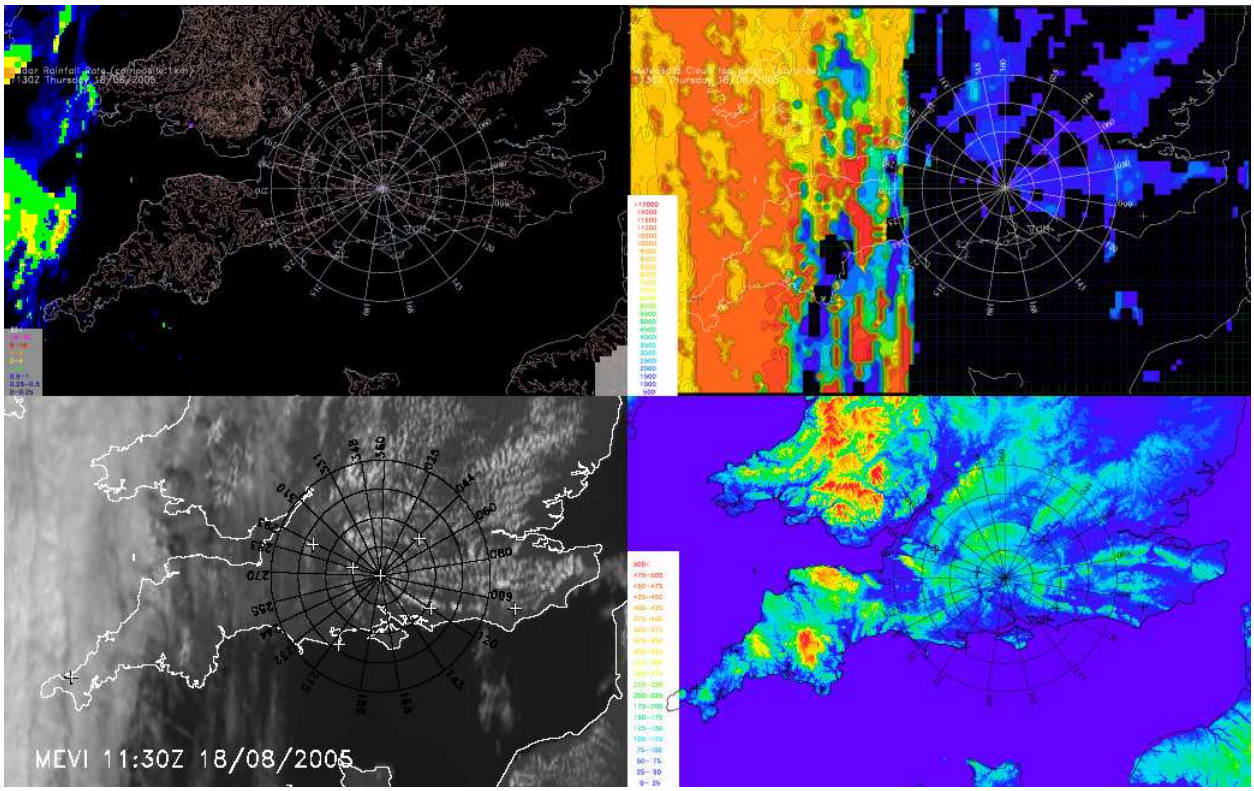


Figure 27 Imagery during IOP 16 at 1130 UTC 18/08/2005. 1/2/5 km radar composite (top left), MSG cloud top height (top right), MSG high resolution visible (bottom left) and orography (bottom right).

The quasi-operational UK 4 km model predicted the location of showers well but the timing was poor (too late). The first precipitation from showers was observed on the network radar at about 1530 UTC. However, the HRTM rerun triggered far too early even in the 4 km model (1130 UTC), suggesting that the later triggering in the UK arose from different initial conditions (00 UTC NAE as opposed to 06 UTC UK MES). The 1 km triggered about half an hour earlier than the 4 km model and produced widespread small scale precipitation as the cumulus developed. This is illustrated in Figure 28.

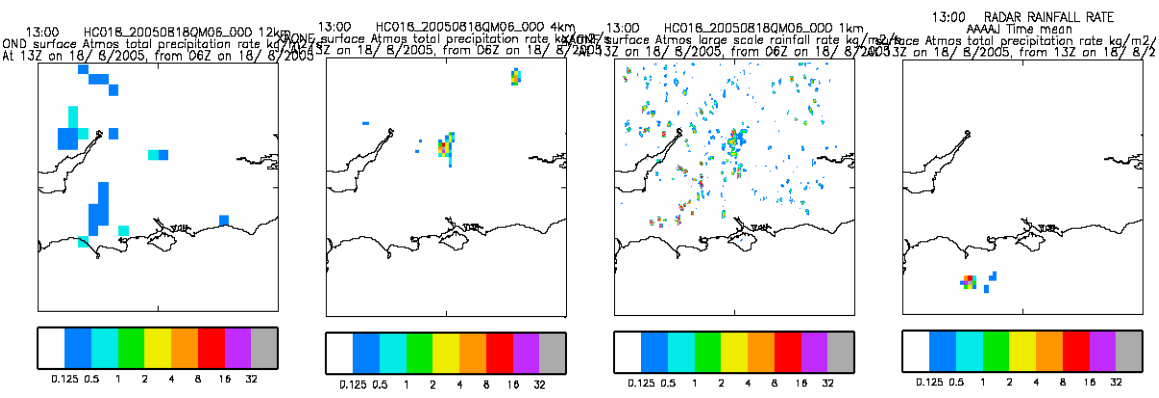


Figure 28 IOP 16 model forecasts of precipitation rate from (left to right) 12 km, 4 km and 1 km models at 1300 UTC from 06 UTC initial conditions, compared with 5 km radar composite (right).

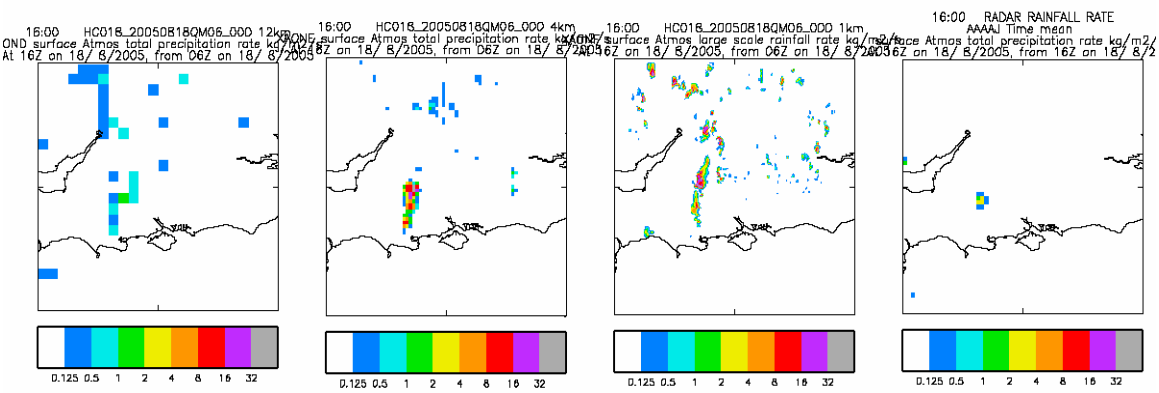


Figure 29 IOP 16 model forecasts of precipitation rate from (left to right) 12 km, 4 km and 1 km models at 1600 UTC from 06 UTC initial conditions, compared with 5 km radar composite (right).

Eventually, a large cluster of cells developed roughly at the right place and time (Figure 29), though the cell in the 1 km model died out at the expense of a spurious cell further north. In this case, the 4 km model performed remarkably well, and it seems at least possible that the early triggering in the 1 km model compromised its development. It is notable that the 12 km model also produced parametrized convection roughly in the right place, though later development is not so good. Figure 29 shows the early stage of development, when the model cells are substantially more active than that observed, but the observed cluster eventually developed into a similar strength storm.

Examination of the wind fields shows that the triggering occurs along a low-level convergence line produced by the meeting of northwesterly flow through the Severn estuary, weak easterly, and a southerly flow off the Channel. It is likely that is corresponds to the observed ADC, and all three models are broadly reproducing this convergence region.

This case provides an excellent example of spurious small scale precipitation in the 1 km model. It may also be useful to assess the accuracy of the frontal cirrus and its impact on surface heating. From a data assimilation point of view the role of MOPS in improving this cirrus should also be evaluated.

4.1.1.8 IOP 17

IOP 17 produced observations of a well-developed cloud head which may be of interest in their own right, but the main convective interest is in the line showers that broke out during the afternoon (from ~1345 UTC) just west of Bath. Good observations of the evolution of CAPE and CIN are available from the sequence of radiosondes. The shower area was well identified by the 00 UTC 12 km mesoscale model, so there should be a good background state for further study.

The higher resolution models trigger close to the correct time and close to, though east of, the correct location (Figure 30). Once more, the 1 km model shows over activity in the small scale rainfall field. They go on to develop heavy showers which drift in the right direction and have roughly the right lifecycle. It seems likely that the (small)

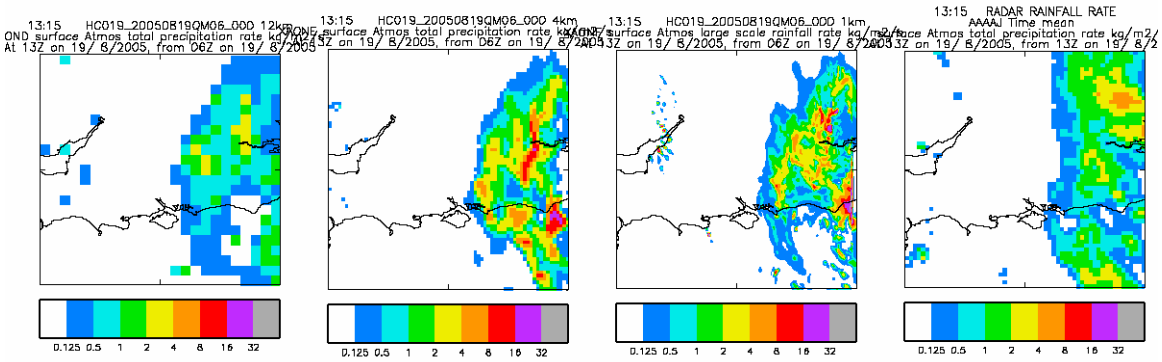


Figure 30 IOP 17 model forecasts of precipitation rate from (left to right) 12 km, 4 km and 1 km models at 1315 UTC from 06 UTC initial conditions, compared with 5 km radar composite (right). First precipitation from showers is visible to the west of the area.

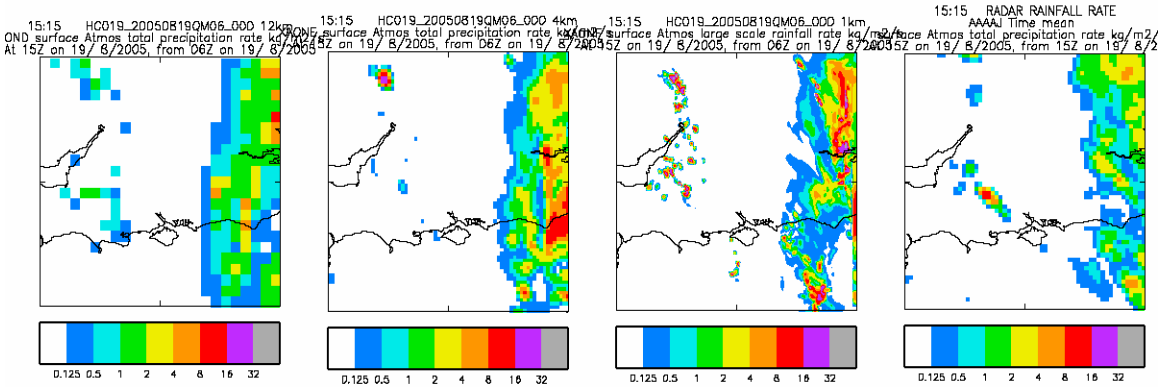


Figure 31 IOP 17 model forecasts of precipitation rate from (left to right) 12 km, 4 km and 1 km models at 1515 UTC from 06 UTC initial conditions, compared with 5 km radar composite (right).

overall location error of the line is associated with slight under-development and miss-location of the cloud head (Figure 31).

Secondary Initiation and Organisation

In addition to much of the above, we assume that secondary initiation depends upon:

- Microphysics, in particular glaciation, transport of precipitation to downdrafts, evaporation.
- Formation and propagation of cold pools/gust fronts – forced by microphysics, controlled by turbulence.
- Gravity waves. Apart from mechanisms generating gravity waves, correct vertical atmospheric structure can be important, and their correct propagation by dynamics is crucial. This raises particular questions in the semi-Lagrangian, semi-implicit formulation.

We are therefore looking for cases with well observed secondary gust fronts (using radar and AWS data) and fairly well modelled initiation (in cases where initiation was not well modelled, there may be scope for interaction with DA work). Again, we would be very interested in collaborating with anyone planning detailed observational analysis of the history of secondary cells. In cases with many cells and multiple generations we shall look at statistical approaches to validation of the model (e.g. do we do a reasonable job of the average cell lifecycle).

IOPs of interest include 6,12 and18 classified α, 7 classified β.

4.1.1.9 IOP 6

IOP 6 was driven by a strong and well-defined upper level cold pool associated with a cut-off low. This was generally very well forecast by the 12 km Mesoscale model, though there were differences in detail. Water vapour imagery suggested that the upper level flow developed a little more rapidly than in the model. Furthermore, leaf-like features appeared in the imagery which were aligned with lines of showers; they may have been caused by the shower organisation or had a role in causing it. Whichever may be the case, it is clear from visible imagery and network radar that the land-sea contrast also had a strong role to play. Lines of showers appeared to emanate from cloud streets originating from the Welsh coast around Anglesey and the Gower Peninsula (Figure 32).

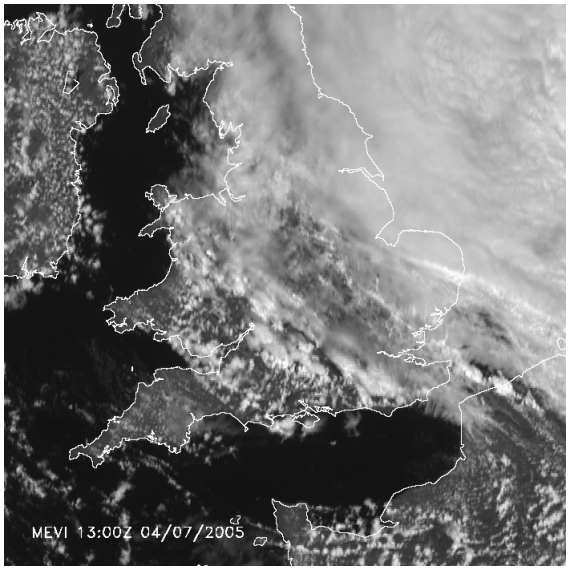


Figure 32 MSG high resolution visible image at 1300 UTC, 04/07/2005, IOP 6

Convergence lines with these origins were apparent in the model forecasts (Figure 33). These were less well defined in the 12 km Mesoscale model but regions of convergence are apparent, and the convection scheme responded to the enhanced instability that resulted. The 4 km model shows very clear lines until they are broken up by the shower outflows, which, as usual, are probably overdone. The 1 km model does not include the source of the convergence but retains it from the boundary forcing. Rather more realistic shower outflow regions are apparent, which may be qualitatively compared with the Chilbolton observation.

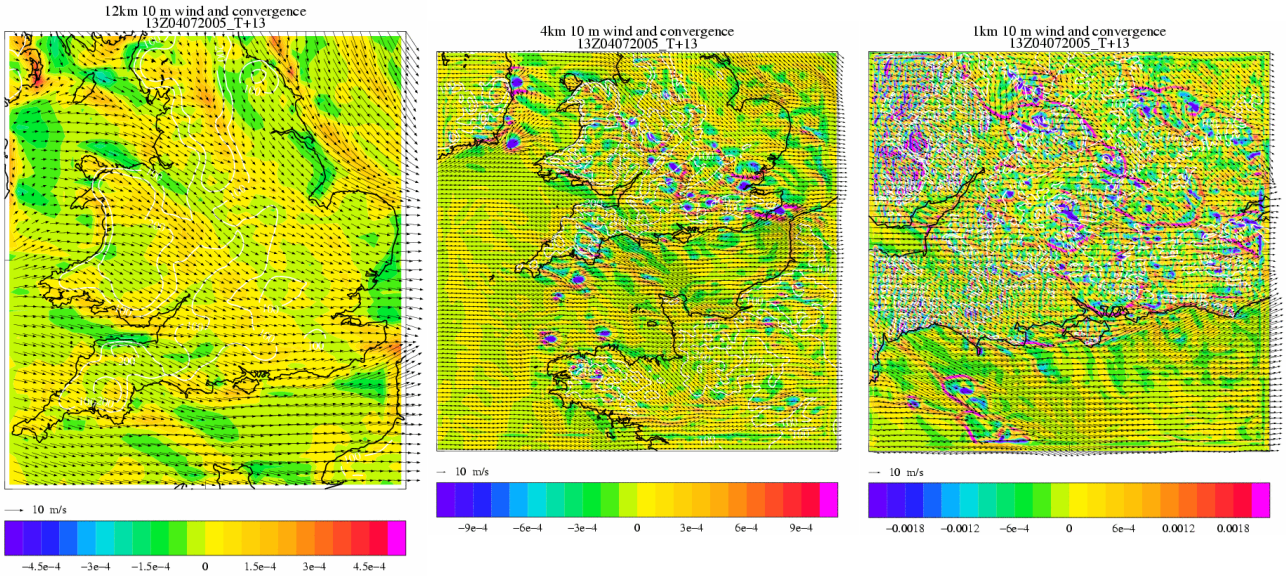


Figure 33 Forecast 10 m wind field and convergence at 1300 UTC, 04/07/2005, IOP 6, from 12 km (left), 4 km (centre) and 1 km (right) models, starting from 0000 UTC analysis.

The moderately strong north-westerly flow produced a fairly steady stream of showers. However, later in the day, fairly large clusters developed, and there is evidence from the Chilbolton radar of gust fronts from individual showers interacting. There is also anecdotal evidence from CSIP observers of hail.

This case represents a case of generally well-forecast, widespread heavy showers, with overall organisation probably associated with topographically induced convergence, but with local secondary initiation probably related to outflows from previous showers. It seems highly unlikely that forecasts, at this stage of development, will reproduce anything other than statistical properties of the cloud field. However, this, in itself, may provide a useful measure of model performance. Cloud size, morphology and microphysical behaviour should all be tested, as well as impact of downdraughts on the near-surface temperature, humidity and wind.

4.1.1.10 IOP 12

IOP 12 is described above in Section 4.1.1.4. The cloud streets that formed within the CSIP area are of dominant interest. However, it is not certain whether the arrangement of these was crucial to the development of the severe storms that subsequently formed as air was forced up the frontal surface. The cloud lifecycle from initial cumulus street to deep storm should be documented. Studies should also establish its sensitivity to parameters affecting boundary layer development.

4.1.1.11 IOP 18

IOP 18 was dominated by a well defined squall line or 'bow-echo' which formed in a broadly westerly flow. The synoptic analysis at 1200 UTC is shown in Figure 34. Convection was dominated by large-scale forcing. An upper-level 'dark zone' is clear in water vapour imagery (Figure 35) and was also captured well by the mesoscale model. However, once intense showers formed, their subsequent evolution was dominated by internal dynamics, primarily associated with propagation of the cold downdraughts. The precursor showers to the squall line formed at around 0815 south of the Mendips and close to or over the Severn estuary beneath this forcing region (Figure 36). The showers existed before this time, having advected in over the sea, but there is clear intensification over land at this time. A line of cloud with tops around 5 km stretches inland from this point and may signify a

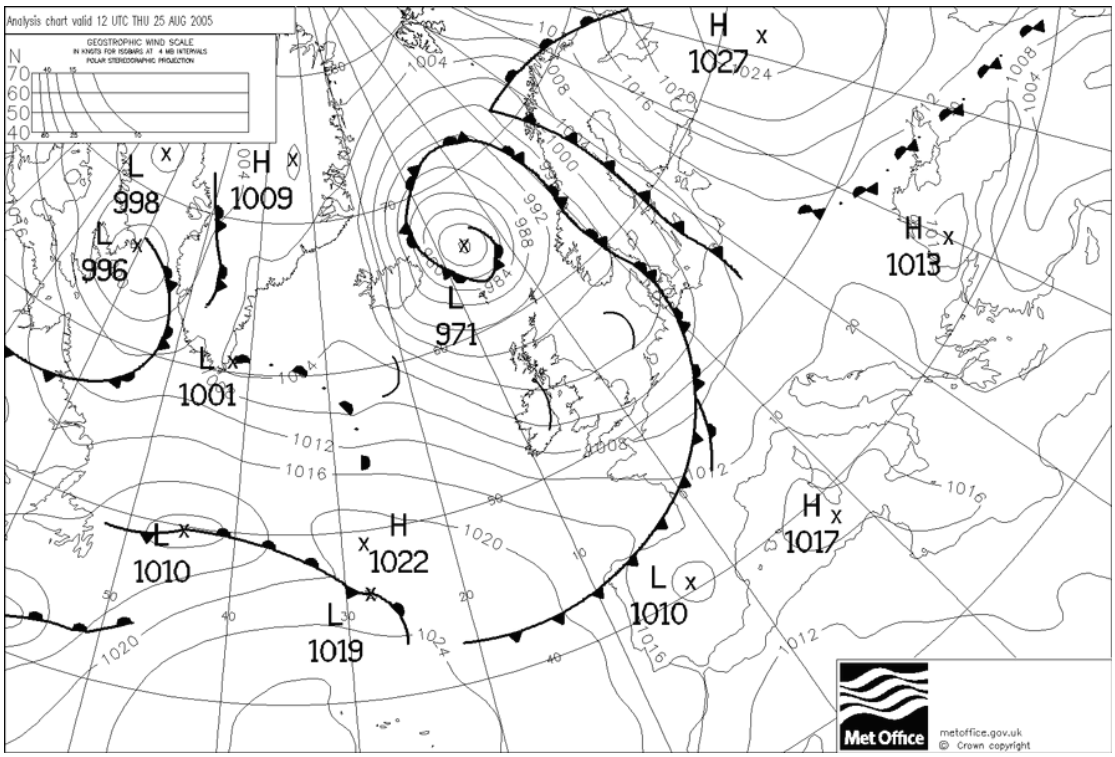


Figure 34 Synoptic analysis at 1200 UTC, 25/08/2005

mesoscale region of convergence and/or moist air.

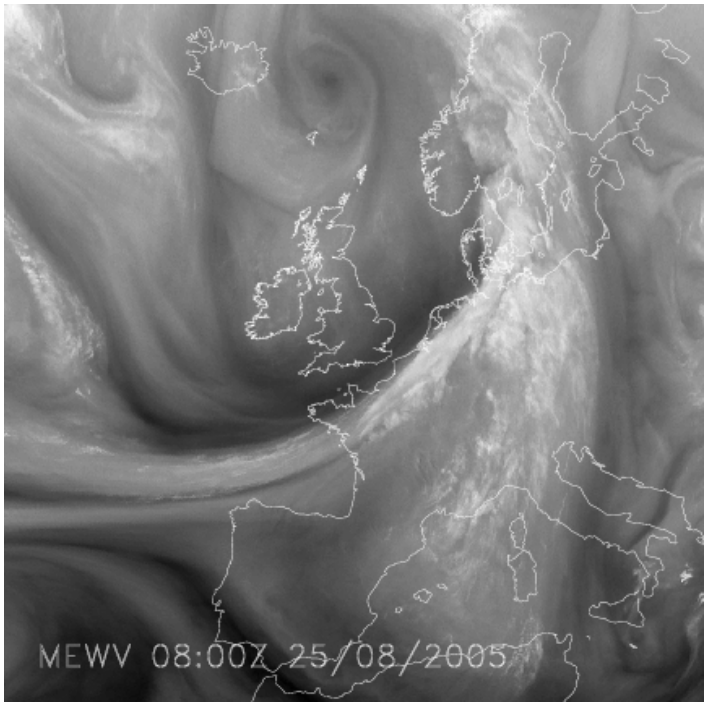


Figure 35 Enhanced MSG Water Vapour image at 0800 UTC, 25/08/2005

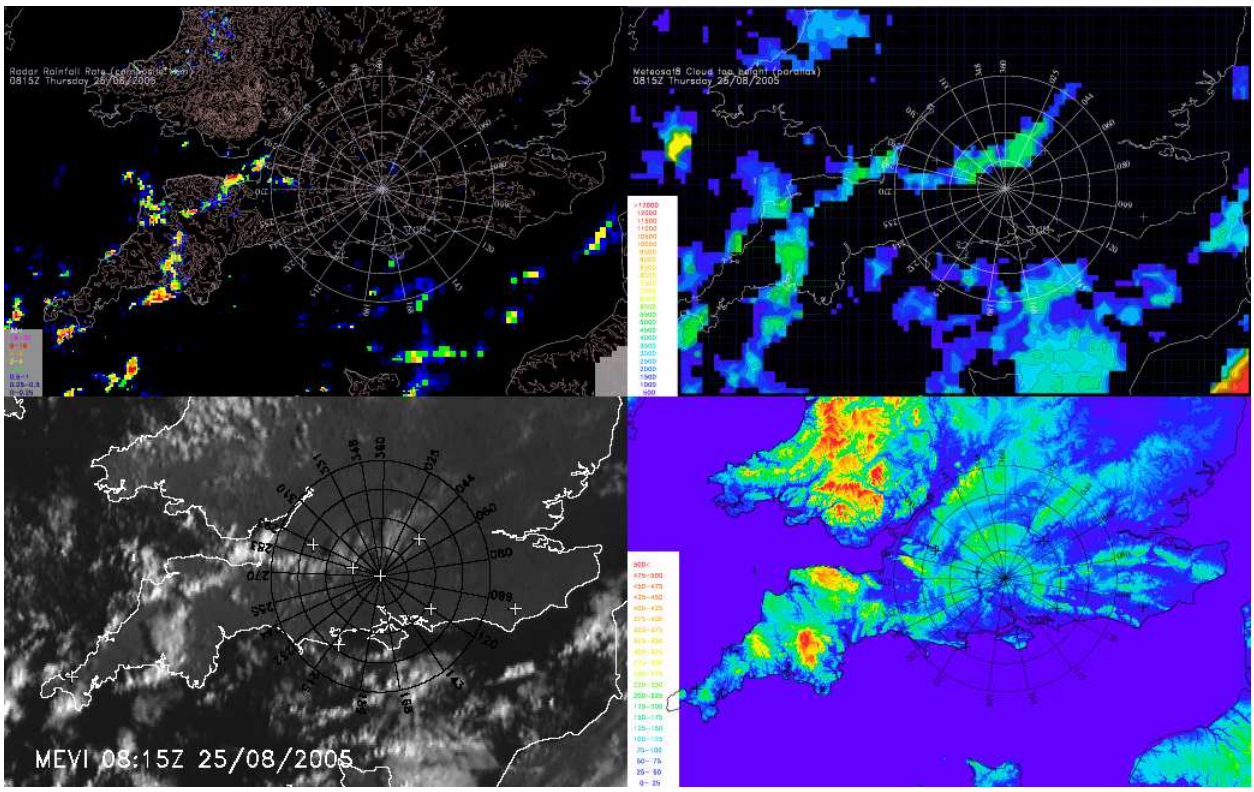


Figure 36 Imagery during IOP 18 at 0815 UTC 25/08/2005. 1/2/5 km radar composite (top left), MSG cloud top height (top right), MSG high resolution visible (bottom left) and orography (bottom right). The initial clouds leading to later organisation are visible over the Severn estuary.

.

These showers go on to form a very well defined line almost 100 km long oriented along a line 60° from north by 1015 UTC. Shortly afterwards the first signs of cells developing ahead of this line is apparent in radar composites, more prominently ahead of the southern half of the line. By 1130 UTC, this forward line dominates and forms a distinct arc which persists for several hours. This forward development occurs as the line tracks though Chilbolton, and so was well observed.

The clear arc is shown at 1230 UTC in Figure 37, which also shows the original showers as a more amorphous area of lighter rain about 50 km behind it. RHI scans from Chilbolton show clear evidence of a density current in the Doppler signal. Figure 37 may be compared with the 120° scan at 1227 UTC which is virtually perpendicular to the bow echo and shows a strong low-level flow away from the radar of at least 15 m s-1, extending up to around 1.5 km. At the head of this is a region of slowly moving air (blue-white in the Doppler velocity) we interpret as the updraught forced by the low level flow. Note that this low level flow extends backwards at least 30 km, with significant but weaker flow behind that.

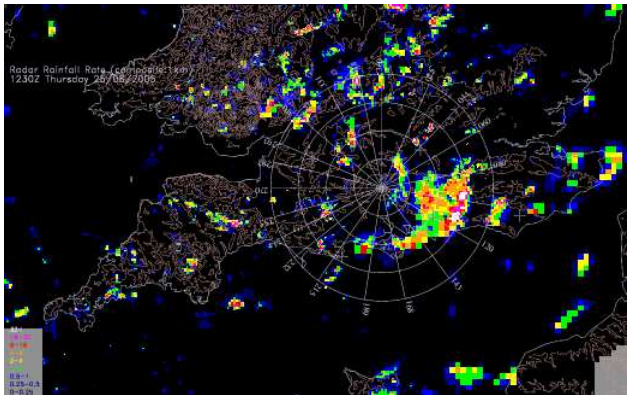


Figure 37 1/2/5 km radar composite rainfall rate from IOP 18, 1230 UTC 25/08/2005. Note organised arc of showers to the SE of Chilbolton.

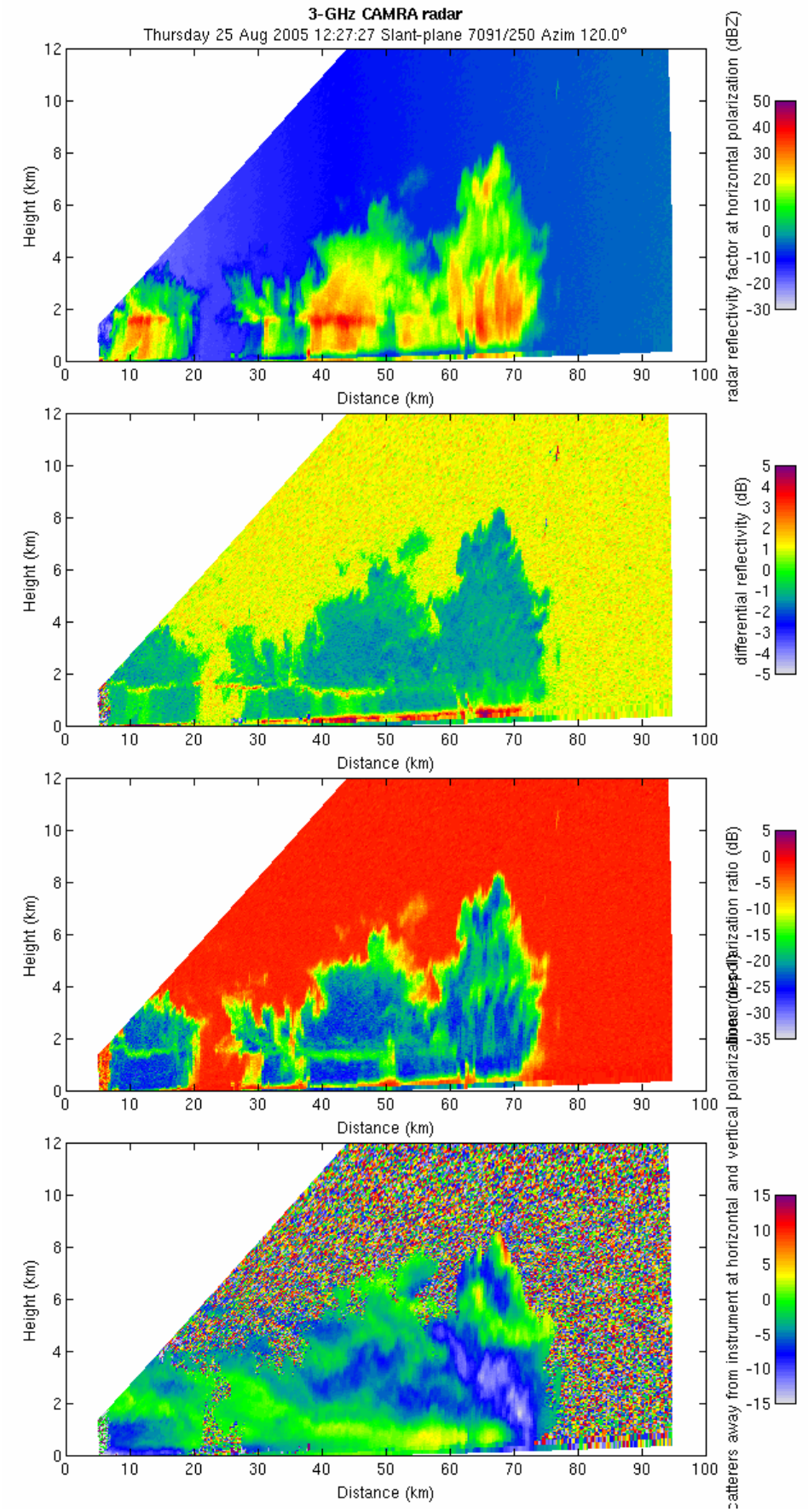


Figure 38 RHI Scan from Chilbolton CAMRA 3 GHz radar at 120° azimuth, at 1227 UTC, showing (top to bottom) reflectivity, differential reflectivity, linear depolarization ratio and doppler velocity. Note this is raw data and the Doppler velocity has an offset: -15 is roughly stationary, 0 about 15 m s^{-1} away from the radar.

The model runs started from 0600 UTC proved remarkably good at both 4 km and 1 km resolution. A shower cluster triggered at approximately the right time and place, with first precipitation at ~0815 UTC in both models, though unlike observations no cloud or precipitation existed prior to this. This may be consistent with the idea that the pre-existing cloud originated over Ireland before the start of the run and was not captured by the model.

Figure 39 shows a short but distinct convergence line along the coast which precedes the first precipitation reaching the surface. A similar, though less distinct, region exists in the 4 km model. By 1030 UTC both 4 and 1 km models have a distinctly linear cluster of showers, though not extending far enough south (Figure 40). The 1 km model also shows the excessive small scale precipitation characteristic of early stage convection in the model identified in section 0. The 12 km model also shows some spatial structure, which, though much less coherent, does appear to drift east with the main cell. Examination of the near-surface temperature, humidity and flow shows a well defined cold, moist pool behind the gust front associated with the precipitation. These develop further to produce remarkably realistic propagating lines of heavy rain (Figure 41). The 1 km model line propagates too quickly, and the 4 km is less distinct and slightly slow.

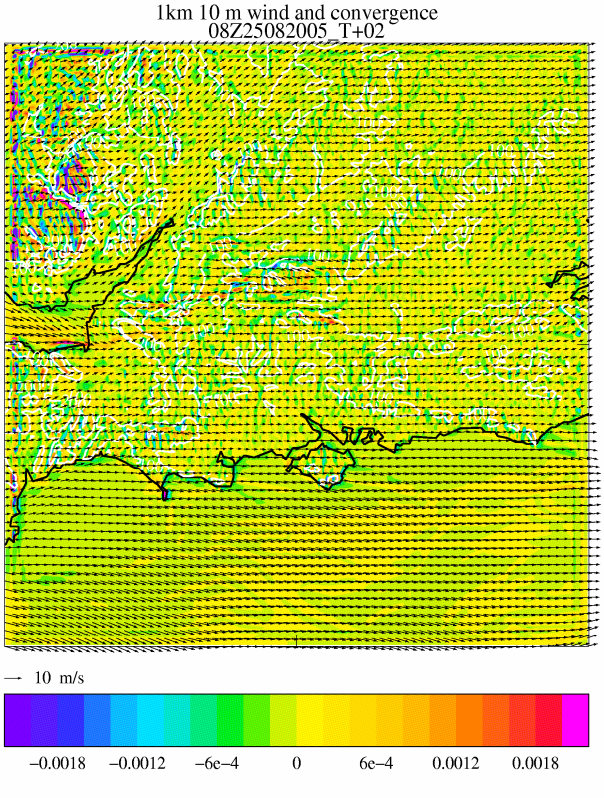


Figure 39 Forecast 10 m wind field and convergence in 1 km model, IOP 18, 0800 UTC 25/08/2005. Note convergence line close to coast over the Severn estuary.

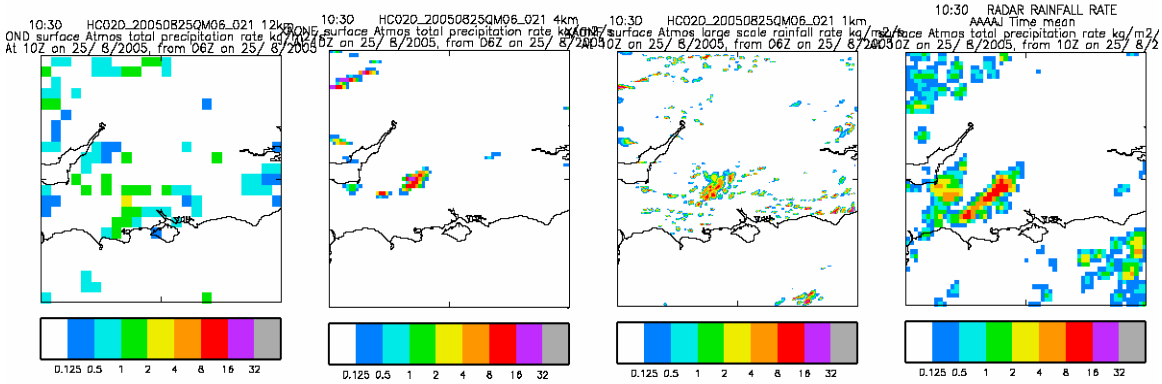


Figure 40 IOP 18 model forecasts of precipitation rate from (left to right) 12 km, 4 km and 1 km models at 1030 UTC from 06 UTC initial conditions, compared with 5 km radar composite (right).

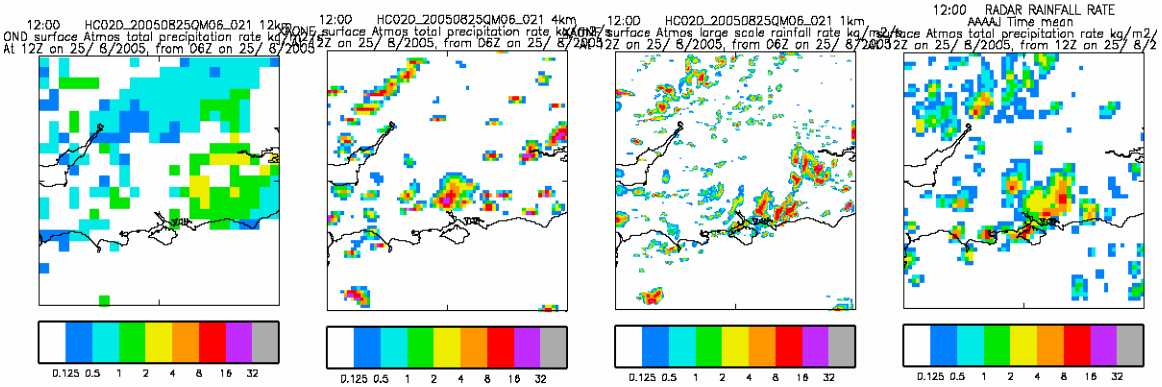


Figure 41 IOP 18 model forecasts of precipitation rate from (left to right) 12 km, 4 km and 1 km models at 1200 UTC from 06 UTC initial conditions, compared with 5 km radar composite (right).

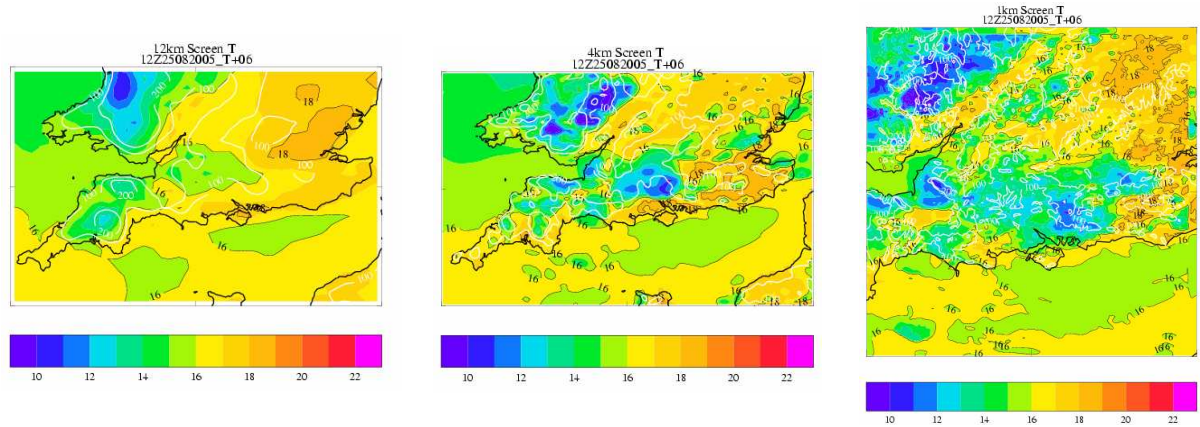


Figure 43 Forecast screen level temperatures for 1200 UTC, 25/08/2005, IOP 18, from 0600 UTC forecast. 12 km (left), 4 km (centre), 1 km (right). Orography contours in white.

Figure 43 shows the forecast screen-level temperatures for 1200 UTC from 12, 4 and 1 km models. The 12 km model primarily shows lower temperatures over orography with only a very weak signal of reduced temperatures over central southern England. The 4 km and 1 km models clearly show mesoscale cold pools behind the precipitation (compare with Figure 41). The 4 km model actually shows slightly greater reduction in temperature, though the 4 km and 1 km are comparable, with drops from above 18 C to around 11 C. This is very close to the temperature drop observed by the AWS at Chilbolton as the squall line passed. A second line is evident near the Welsh border which also verified well. Cross sections through the squall line show considerable variability along it, but a typical section (Figure 42) may be compared with Figure 38.

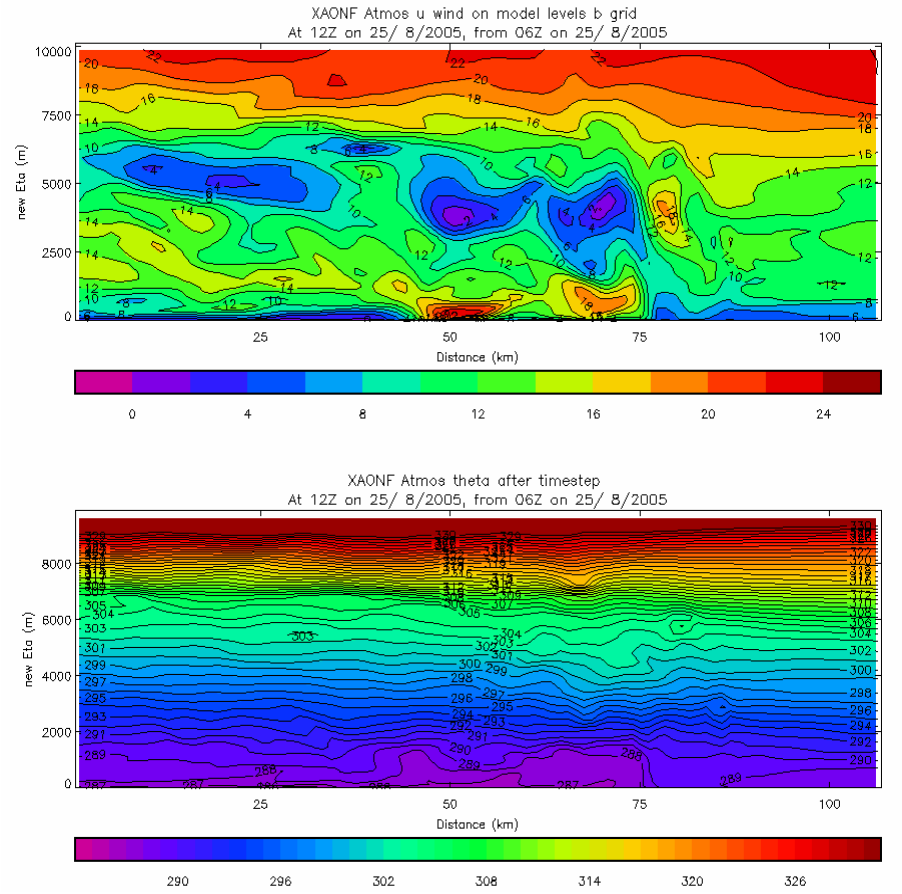


Figure 42 Cross section through 1 km forecast at 1200 UTC 25/08/2005 from 0600 UTC run. The cross section is taken through the squall line and shows wind speed along the section (top) and potential temperature (bottom).

The initiation of the main squall line is of interest in this case, but unfortunately lay outside the CSIP domain, so very little non standard data is available. The development of the squall line is driven by cooling by evaporation or melting of precipitation, so the sensitivity of this case to microphysics is of interest. The role of the turbulence scheme in controlling the detailed behaviour of the gust front is also of interest.

4.1.1.12 IOP 7

IOP 7 was characterised by horseshoe rings of showers which appear to spread south over the CSIP area from northern England (Figure 44). It has been hypothesised that this organisation is due to gravity wave propagation from primary storms further north, though the possibility of a gust-front originating from the shower over

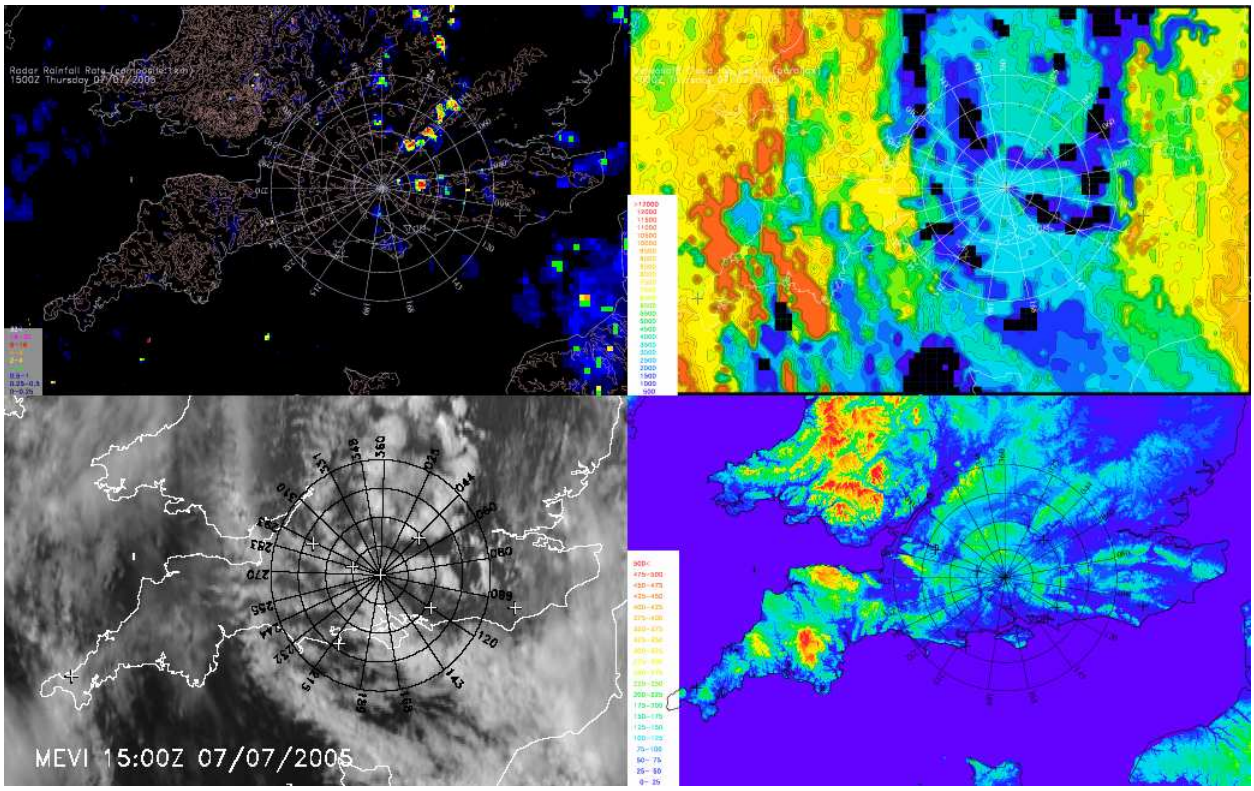


Figure 44 Imagery during IOP 7 at 1500 UTC 07/07/2005. 1/2/5 km radar composite (top left), MSG cloud top height (top right), MSG high resolution visible (bottom left) and orography (bottom right). A horseshoe shaped ring of showers is visible with further cloud bands ahead.

Humberside should not be ruled out.

Model forecasts are qualitatively quite reasonable, if rather overdone in intensity. However, while a large scale band is apparent (Figure 45, which may be compared with Figure 44), probably associated with the upper level PV structure, there is no obvious evidence of the horseshoe rings of showers apparent in imagery. This may be because they originate outside the 1 km domain and the 4 km model cannot support them properly, but further study will be required to establish both their cause and why the model does not show similar behaviour.

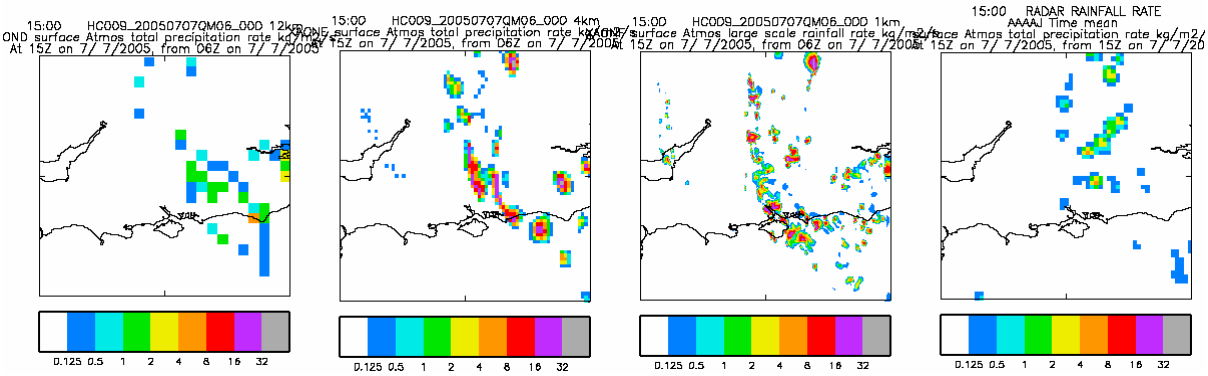


Figure 45 IOP 7 model forecasts of precipitation rate from (left to right) 12 km, 4 km and 1 km models at 1500 UTC from 06 UTC initial conditions, compared with 5 km radar composite (right).

4.1.1.13 IOP 3

IOP 3 should be mentioned as an unusual case for CSIP, though not so unusual for extreme summer time convective precipitation. There is clear evidence from the Chilbolton radar that initiation took place at mid-levels, with bases at about 2.5 km. Indeed, there is strong evidence of multiple stable layers beneath convective cloud in the early stages. Further analysis is required to confirm the precise situation, but there are certainly some features in common with the 'Spanish Plume'. Figure 46 shows the vertical profile at 1201 UTC from Larkhill, with a fairly shallow well-mixed boundary layer beneath a deep dry layer up to 800 hPa.

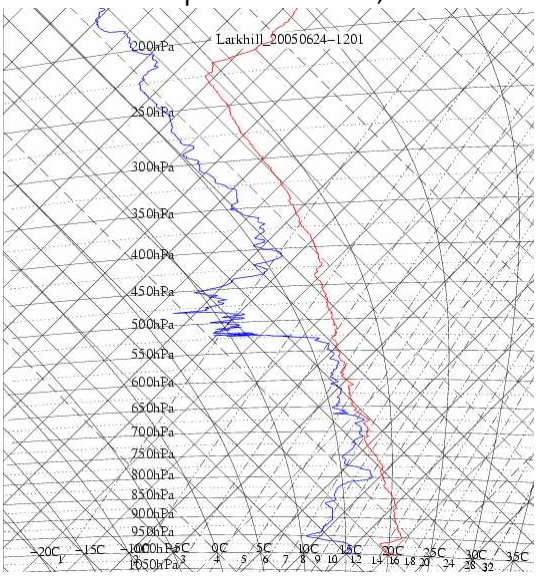


Figure 46 Radiosonde ascent at 1201 UTC, 24/06/2005, IOP 3

Although all models produced intense rain over wide areas of England, model performance was poor in detail. The best that could be said, perhaps, is that some of the morphology of behaviour was reproduced, though it was noticeable that intense lines of convection, propagating very rapidly south when initially formed, and advecting eastwards, were not represented especially well. Figure 48 shows that the models developed a very narrow line of intense rain early in the forecast (0900UTC) which corresponds roughly with the radar but is much too narrow, with little evidence of more widespread, lighter rain. By 1300 UTC, the original band has weakened and drifted out of the area to the E, whereas in the models it has broadened and only drifted a little, to be joined by a second band from the west which might (with the eye of faith) be identified with the band actually present in the radar (Figure 47).

Given the dominance of large scale uplift coupled with mesoscale variability and lack of surface forcing, the lack of quality is not surprising, but this case should not be forgotten as it represents an important class of eve

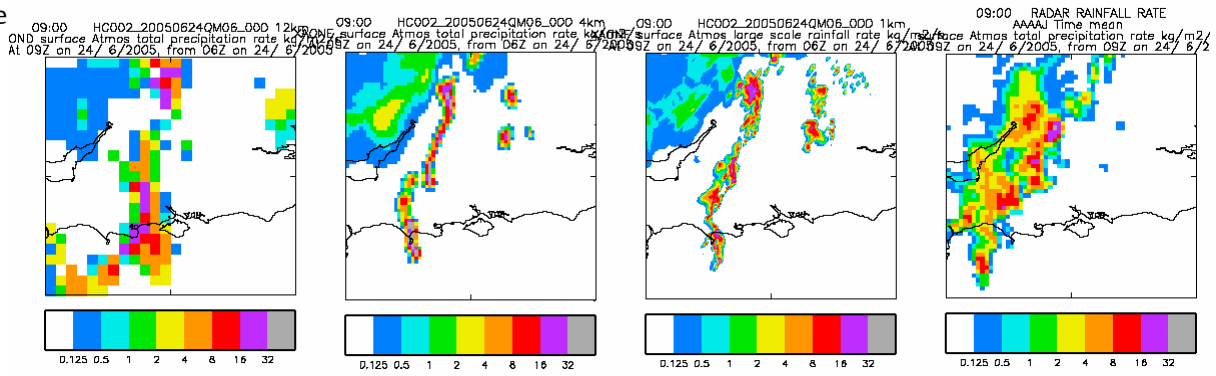


Figure 48 IOP 3 model forecasts of precipitation rate from (left to right) 12 km, 4 km and 1 km models at 0900 UTC from 06 UTC initial conditions, compared with 5 km radar composite (right).

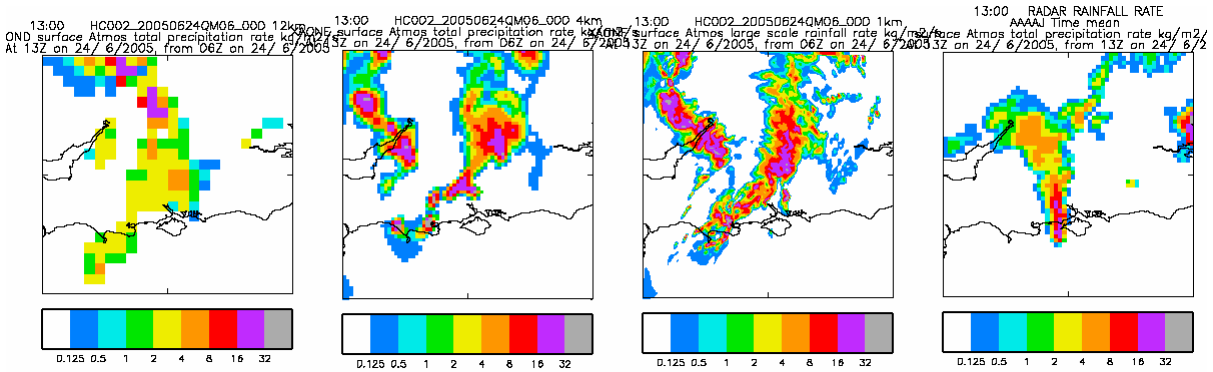


Figure 47 IOP 3 model forecasts of precipitation rate from (left to right) 12 km, 4 km and 1 km models at 1300 UTC from 06 UTC initial conditions, compared with 5 km radar composite (right).

4.2 Mesoscale Data Assimilation

Interests, at least in the short term, are focussed on understanding and evaluating the impact data assimilation is having on the model state. Particular issues are the behaviour and improvement of the assimilation of cloud and precipitation data (currently through MOPS/LHN) and the assimilation of Doppler wind data, though the performance of the conventional 3DVAR assimilation system also needs careful evaluation, especially where convergence lines or cold pools are evident in data. The results shown here did not include DA at high resolution, so the comments below are of necessity cursory, indicating which cases may be best for addressing particular questions but without, of course, any confirmation.

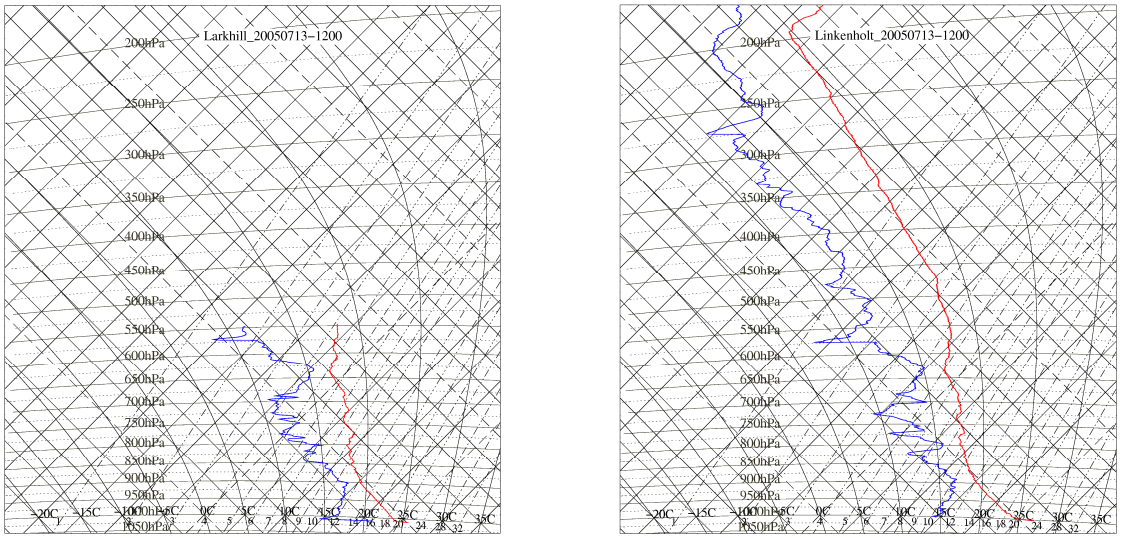


Figure 49 Radiosonde profiles from sondes released at Larkhill (left) and Linkenholt (right) at 1200 UTC, 13/07/2005, IOP 8

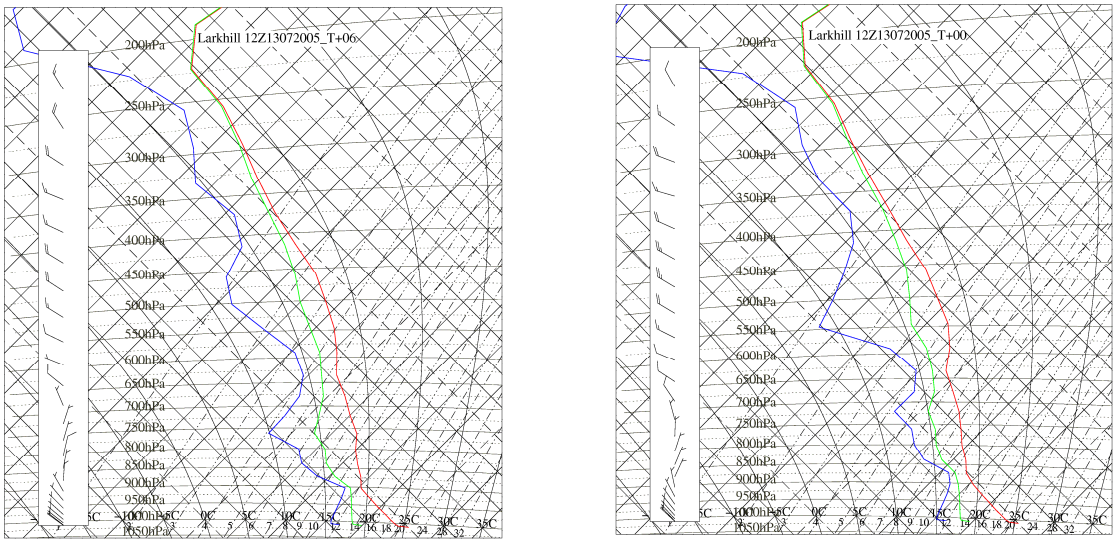


Figure 5012 km Mesoscale model profiles at 1200 UTC 13/07/2005, IOP 8, from 0600 run (6 hour forecast, left) and 1200 UTC run (right).

Assimilation of Conventional Data

Additional Met Office soundings should have been used in the operational DA system. If not, they could be (and vice-versa). The impact of existing DA should be evaluated by comparison with additional CSIP data, primarily sondes, profilers and AWS data. Particular interest is in vertical structure (especially lids), convergence lines and low level moisture.

Many of the same cases used to study boundary layer evolution will probably be of value here. IOP 18 will be of interest to evaluate impact of surface observations, given very strong cold pool. IOP 8 provides a good example of problems with boundary layer moisture in a low wind, surface forced situation. The 1200 UTC Larkhill and Linkenholt (roughly 20 km N) soundings are shown in Figure 49. These may be compared with 12 km

operational mesoscale model Larkhill profiles at T+6 from the 0600 UTC run and T+0 from the 1200 UTC run (Figure 50). It is evident that both model soundings are significantly drier in the boundary layer than observed at the same location (by of order 10%), though more similar to the profile at Linkenholt. It is also notable that above the boundary layer, given the limitations of resolution, the T+0 profile is close to perfect, and both it and the T+6 profile are extremely good for temperature in the boundary layer, but the T+0 humidity in the boundary layer is actually drier than the T+6. This suggests than something arising from data assimilation had contributed to dryness of the boundary layer, and, at the very least, the assimilation system had failed to correct the boundary layer moisture. The model backgrounds do suggest that a significant gradient in humidity was present; this is not unusual and the ability of the DA system to retain and improve such gradients should be studied.

Assimilation of Cloud and Precipitation

Questions of interest are:

- Impact of MOPS on boundary layer cloud prior to initiation. Same cases as studied within BL development. In particular, IOPs 5, 8 and 16 may provide useful tests of MOPS cloud analysis, especially high cloud.
- Ability of system to make small changes in triggering (time or space). Ideally, this needs well, but not perfectly, forecast primary or (if we are lucky, secondary) initiation. IOP 18 may provide a good case.
- Ability of the system to make significant changes in location. IOP 9 may provide a simple test case.
- IOP 3 is a good example of mid-level instability and a poor, very intense, forecast. The behaviour of MOPS and LHN should be tested in this case.

4.2.1.1 IOP 9

IOP 9 was an example of well organised line convection associated with a cold front. As such, it was un-spectacular, but the overall character of the precipitation was extremely well forecast (Figure 51).

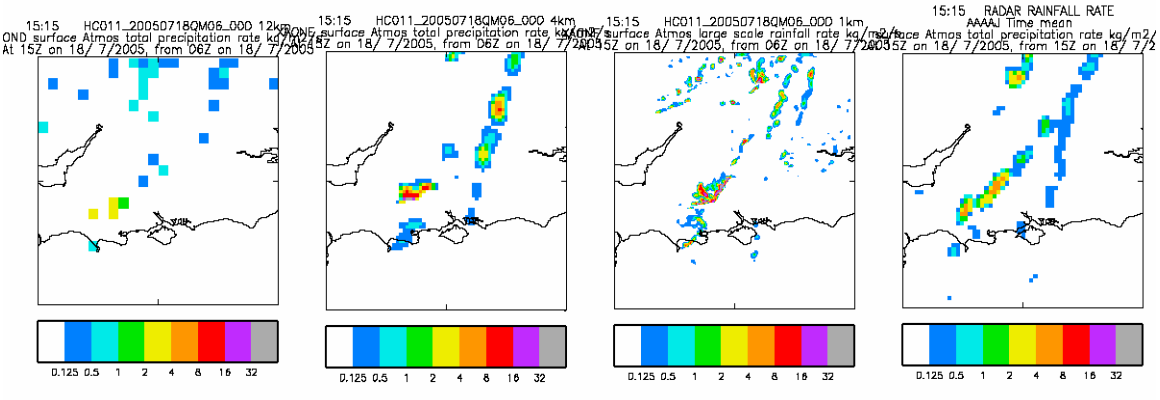


Figure 51 IOP 9 model forecasts of precipitation rate from (left to right) 12 km, 4 km and 1 km models at 1515 UTC from 06 UTC initial conditions, compared with 5 km radar composite (right).

There is evidence of low level convergence in the model data – there may also, therefore, be interest from the point of view of Doppler wind. However, the first question is how well the assimilation system may assimilate precipitation data to make small adjustments to position, and at the same time how well the associated dynamics respond.

Assimilation of Doppler wind

All cases with useable Doppler data are probably of interest, in conjunction with the above, but any Doppler data with well defined convergence lines would take priority, as this will enable clear impacts to be evaluated. IOP 18 certainly has well defined gust front. IOP 9 may be a nice case in view of its simple 2D frontal line convergence. IOP 6 shows small scale gust fronts between some later storms. Others have yet to be identified.

5 Summary

The following table summarises the above comments for each IOP. The forecast quality is a subjective assessment of how well the HRTM performed. Experience suggests that a reasonably good performance is a useful prerequisite for model improvement, as poor performance often reflects large scale errors we cannot hope to correct in this system.

At this stage, one consistent signal emerges regarding model performance. In every case of relevance, the 1 km model produces a great deal of small-scale precipitation from what should be essentially shallow cumulus. This is consistent with previous results from idealised studies. While cloud microphysics might have some role to play, the treatment of vertical and horizontal mixing is crucial in controlling this behaviour. The 4 km model does not suffer in the same way, perhaps because the convection scheme is treating shallow cumulus, perhaps because of additional numerical dissipation, but an analogous problem occurs in the form of excessive precipitation one the large cells the model produces do form. It seems likely that errors are compensating somewhat in the 4 km model, so improvements will have to be assessed with care.

IOP	Date	Forecast Quality	Comment
Primary initiation and boundary layer development			
1	15/06/2005	***	Surface convergence and upper level forcing.
5	29/06/2005	**	Precise role of large scale forcing, low level topography and impact of cloud.
8	13/07/2005	**	Development of cumulus, role of orography and sea breeze. Model over-forecast.
12	28/07/2005	**/***	Cloud streets: temporal development, role in triggering.
13	01/08/2005	***	Why some deep clouds?
14R	11/08/2005	*/**	Mechanism for convergence line.
16	18/08/2005	**	ADC, Convergence Line, Cirrus impact on SEB
17	19/08/2005	**	Evolution of CAPE and CIN
Secondary Initiation and Organisation			
6	04/07/2005	*/**	Complex multiple downdraught interactions. (May need more statistical approach?)
7	07/07/2005	**	Role of gravity waves?
12	28/07/2005	**/***	Interaction between cells, large scale forcing may have problems.
18	15/08/2005	****	Cold pool dynamics, microphysics, why so predictable?
3	24/06/2005	*	Mid-level, intense precipiotation.
Assimilation of Conventional Data			
8	13/07/2005	**	Assimilation of surface and sonde humidities.
18	25/08/2005	****	Ability of surface data to retain and improve cold pool and gust front.
Assimilation of Cloud and Precipitation			
5	29/06/2005	**	Impact of MOPS cloud on surface heating.
8	13/07/2005	**	Assimilation of cumulus. How does MOPS handle this?
9	18/07/2005	***	Well defined line convection with surface contrast.
16	18/08/2005	**	Impact of MOPS on cirrus and hence surface forcing.
18	25/08/2005	****	Initiation of cells. Ability of data to retain and improve cold pool and gust front
3	24/06/2005	*	Impact of MOPS/LHN on mid-level instability.
Assimilation of Doppler wind			
6	04/07/2005	*/**	Possible small scale gust fronts in Doppler data.
18	25/08/2005	****	Ability of data to retain and improve gust front

6 Overall priority list (subject to amendment!)

We recommend the following priority list for general analysis:

1. IOP 1 – this is, at least on the basis of initial analysis, a very straightforward case which was well forecast, but which showed characteristic model error in small scale structure.
2. IOP 18 - this case was remarkably well forecast at high resolution, though with some errors in evolution which should form a good test of both model physics and all aspects of data assimilation. There is therefore interest from all areas.
3. IOP 12 – again, remarkably well forecast in general at 1 km, with interesting boundary layer dynamics contributing to initiation.
4. IOP 8 – classical development of Cu capped boundary layer, with variations coming from humidity gradients, orography and land/sea contrast. Very little large scale advection. Some DA interest from the point of view of assimilation of moisture data.
5. IOP 5 – Complex interaction between processes. Role of cloud in surface energy balance.
6. IOP 16 – Impact of cloud on surface energy balance and area of deeper convection (ADC).
7. IOP 17 – General boundary layer development.
8. IOP 6 – Statistical study of scattered, heavy showers from NW. Some possible interest from DA.
9. IOP 3 – Poorly forecast, but a possible test for DA.

7 References

Browning, K.A., et al, 2006, A Summary of Convective Storm Initiation Project Intensive Observation Periods. Forecasting Research Technical Report No. 474, JCMM Report No. 153.

8 Appendix

IOP	Date	Comments	Forcing and triggering	12 km Model Performance	4 km Model Performance	1 km Model Performance	Overall Comments
1	15/06/2005	Triggering over SW peninsula convergence possibly modulated by upper trough. Alpha.	Convergence line, SW peninsula. Probably sea breeze.	Random over SW Peninsula, including correct location too early (08:30). Picks out downstream line. Doesn't penetrate lid at 700-750 hPa.	Very good location and timing. Triggers early (08:30? cf 09:15), very close to correct location. Some spurious excess over Cornwall.	Very good location and timing. Excessive small scale triggering and too linear. Triggers early (08:30? cf 09:15) and resulting storm is therefore too far downstream (< 30 km).	Very good 4 and 1 km forecasts, main problem being excessive small scale precipitation in 1 km. Cause of convergence line. Role of upper level forcing?
2	19/06/2005	Yorkshire floods - no triggering in CSIP area. Gamma.			False alarm in UK 4 km.		Reason for false alarm in UK model,
3	24/06/2005	Glastonbury floods. Upper front, organised N-S lines of convection. Beta.	No obvious low level triggering	Loses main system after 11 Z over Bedfordshire. Hint of linear organisation in second line (Dorset, 1130). Mid-level triggered (if at all).	Strong linear structures, but generally very poor location.	Largely follows 4 km.	Very complex evolution, poorly forecast at small scale. Deserves study but will be very difficult.
4	28/06/2005	Large scale organised ('spiral') bands around low centre. Gamma.	No obvious low level triggering, though likely cold pool/subsidence zone later (1900Z)		Not yet run.	Not yet run.	

IOP	Date	Comments	Forcing and triggering	12 km Model Performance	4 km Model Performance	1 km Model Performance	Overall Comments
5	29/06/2005	Oxford flood - organised E-W line associated with upper level forcing or cirrus modulated surface forcing. Alpha.	Uncertain role of cirrus in modulating surface heating. Possible frontogenesis? CIN early in day. Also mid-level lid (650 hPa).	Spurious convection over most of southern England by 13Z, spreading from SW. Band in right place ~1245Z but also spurious closer to coast.	Spurious, probably shallowish, convection new S coast ~10Z, goes on to form band a little too far N at ~12Z. Clear surface convergence at 10Z precursor to precipitation.	Much spurious, probably shallowish convection near S coast ~10 Z goes on to form band a little too far N (~30 km) at ~12Z, similar to 4 km. Band also moves N too fast. Spurious small scale convection continues throughout forecast.	Generally good 4 km and 1 km forecasts except for small scale triggering of 1 km and location of band too far N. More correct location of band in 12 km model may suggest upper level forcing is of more relevance. Role of cirrus?
6	04/07/2005	Continuous stream of cells originating in NW flow over Wales, with some triggering and organisation in CSIP area. Alpha.	Clear Land surface forcing, with help from convergence lines. No CIN, weakish CAPE.	Picks up convergence from Anglesey and Pembroke well. Main problem is Welsh coast. V good accumulations. All models have slight positional error of residual low/cloud head.	Generally good location.	Generally good location, though excessive.	Some question over small phase error in large scale position of cold pool contaminating results. Otherwise 1 km model will benefit from larger domain including Wales to pick up role of coast and orography in forming convergence lines. It would also appear that some convergence lines in the model generated cells which did not exist in reality - why? Secondary initiation will be major interest in 1 km model.

IOP	Date	Comments	Forcing and triggering	12 km Model Performance	4 km Model Performance	1 km Model Performance	Overall Comments
7	07/07/2005	Showers in N flow. Beta.	No obvious surface forcing apart from edge of warmer air (cloud cover). John Marsham suspects GW. Weak CCB ascent?	Much more linear (N-S) than actual. Otherwise, generally sensible. No obvious cold pool till (possible) weak signal late in forecast.	Much more linear (N-S) than actual. Otherwise, generally sensible. Strong convergence down spine of England - difficult to distinguish from convection. Clear cold pool associated with line of showers (15Z)	Clear cold pool behind line of showers (15Z). Far too much rain and too much small scale convection.	Appears closely coupled to upper level PV. John Marsham has hypothesised modulation by GW from Yorkshire, which appears absent from the model. Would need V large domain.
8	13/07/2005	Surface forced along Chilterns, S coast sea breeze, intermediate lid and little triggering. Alpha.	Very obvious surface and orographic forcing.	Overdone. Overall, 12/4/1/pretty similar	Overdone. Clear sea breeze convergence lines, one in right place for actual triggering.	Overdone.	Likely to be a very good test for boundary layer/Cumulus treatment in model. Currently not very good, though whether this is physics or initial state requires analysis. Likely to be sensitive to BL moisture.
9	18/07/2005	A narrow line of convective showers associated with the passage of a surface cold front. Alpha.		Overdone convective precip to N on front.	Overdone convective precip to N on front.	Good line structures. Cold pool formed later (17Z) and pushed convection ahead of front.	Potentially a good DA example - small location errors. Is the cold pool realistic?

IOP	Date	Comments	Forcing and triggering	12 km Model Performance	4 km Model Performance	1 km Model Performance	Overall Comments
10	23/07/2005	Isolated showers eventually breaking out late in day after suppression by lid at 2 km. Gamma.		Overdone convective precipitation.	Overdone convective precipitation.	Overdone convective precipitation.	Need to establish whether forecast precip was breaking through lid because lid was too weak relative to surface forcing, or simply that shallow convection produced too much precipitation.
11	24/07/2005	Beta.		Main problem seems to be error in location of low centre, leading to substantial displacement of convective bands to North. Applies to all models.			Should look at impact of DA on later runs. Otherwise, probably of low interest.
12	28/07/2005	Cloud Streets from S Coast, Birmingham tornado. Alpha.	Clearly related to BL development, then dry intrusion overrunning cold front.	Excessive convection in dry slot, too little at front.	Good individual cells forced by convergence line and uplift.	Picks out cloud streets and general development. Main clouds out of area.	Trigger mechanism for main tornadic cells of interest as well as role of cloud streets. main cell located close to triple point. Need larger area 1 km run.
13	01/08/2005	S Coast and Kent/Sussex initiation, intermediate lid with only 1 or 2 cells going deep to ~9 km. Beta.	Surface forced. No CIN.	All models very comparable (and pretty good)	4 km adds little.	1 km adds little.	Why do some cells manage to go deep?

IOP	Date	Comments	Forcing and triggering	12 km Model Performance	4 km Model Performance	1 km Model Performance	Overall Comments
14	11/08/2005	Retrospective IOP - no full operation. Isolated shower - possible sea breeze or upper level triggering. Beta.		General area pretty good if a little E. All models very comparable.	Location good. Possible convergence lines.	Excessive triggering, location good. Possible convergence lines.	Earlier forecast was poor - indicated strong lid. What changed? What was the role of low level convergence lines.
15	13/08/2005	Shallow showers behind cold front. Gamma.					
16	18/08/2005	Weak, broadly southerly flow ahead of a band of cold-frontal rain advancing slowly from the west. Shallow showers developing later in evening. Beta.	Lid lifting from west.	Develops too early. Otherwise, very good. All models very comparable.	Develops too early(1130Z first cells, secondary development in right place at 1345Z cf 1530Z). Complex network of convergence lines.	Develops too early (11Z first cells, secondary development in right place at ~1315 cf 1530Z). Usual small scale showers.	Why too early? Why right place (role and cause of convergence line)? 12 km parametrized shows similar good location. Role of Cirrus in suppressing triggering.

IOP	Date	Comments	Forcing and triggering	12 km Model Performance	4 km Model Performance	1 km Model Performance	Overall Comments
17	19/08/2005	Scattered showers in Wales and the north-west Midlands in the north-westerly flow behind Cloud Head(s) during the early afternoon, followed by the formation of a line of showers just west of Bath. Beta.	Likely surface convergence.	Location and timing not bad.	Location and timing reasonable, though suspicion is that actual cells in model do not correspond with actual cells - there is a hint of weak cells in the right place which die out. These are associated with a clear low level convergence line.	Similar to 4 km.	Mechanism for triggering. Why do cells on convergence line die out? Needs larger domain 1 km.
18	25/08/2005	Westerly flow beneath upper trough - development of organised convection with strong cold pool/subsidence/gust front system. Alpha.		Triggers over land far too soon. Propagates too fast E. No cold pool.	Triggers ~0815 over Bristol Channel just S of Weston-super-Mare cf earlier triggering to W in reality, though there is clear intensification as cells reach this point. Reality has linear structure by 0900, but model still has main cell in right place. Good subsidence behind organised system. Superb cold pool, though propagates too slow.	Triggers ~0800 over Bristol Channel just S of Weston-super-Mare cf earlier triggering to W in reality, though there is clear intensification as cells reach this point. Reality has linear structure by 0900, but model still has main cell in right place. Good cold pool, though propagates too fast and rather ragged. Suggestion of splitting.	Mechanism for primary triggering and formation of linear structure. Rate of cold pool propagation. Sensitivity to microphysics and turbulence schemes. Possible experiments with convection scheme in 4 km model.